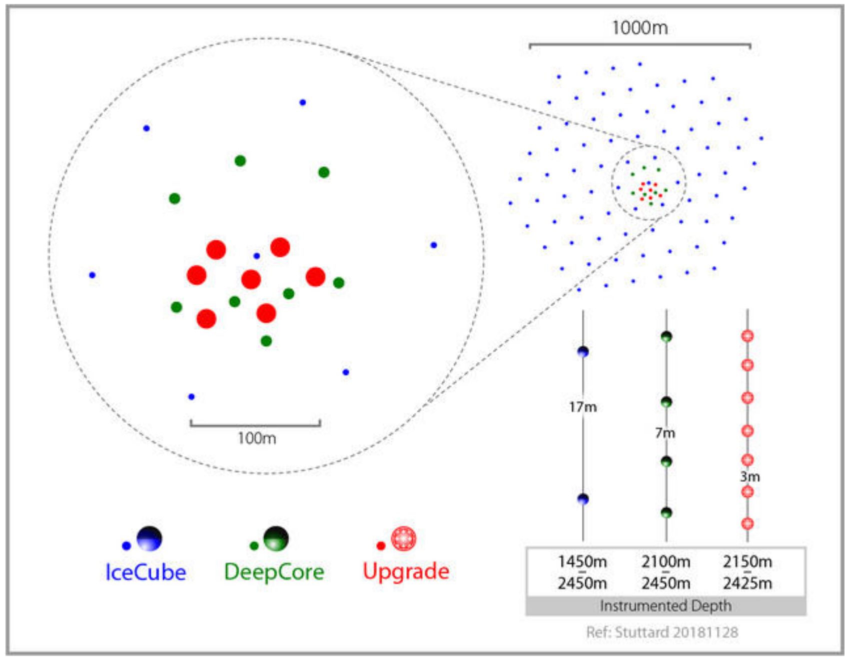
Measuring Neutrino Oscillation Parameters With Atmospheric Neutrinos *This Decade*

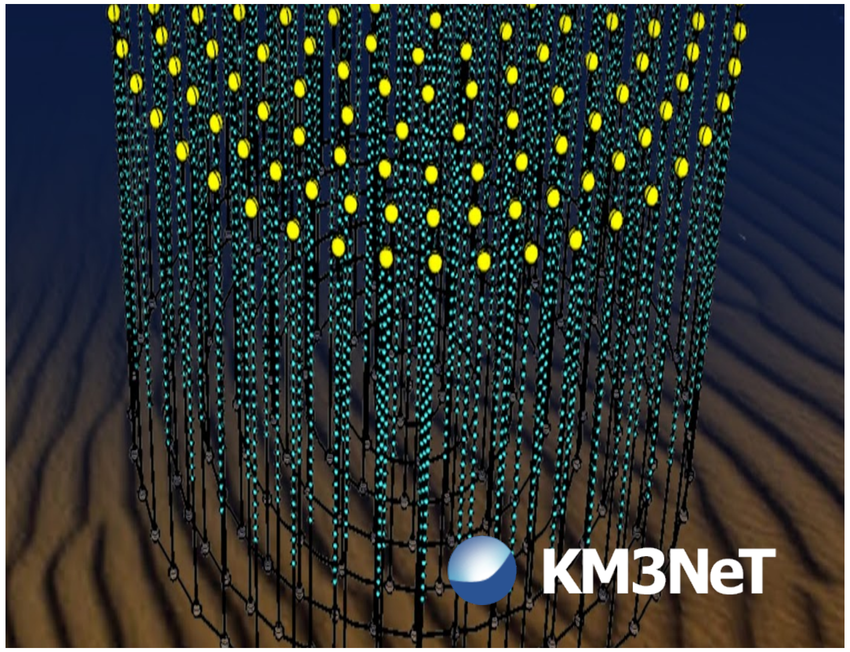
- Atmospheric neutrino experiments have played a central part in the discovery of neutrino oscillations.
- **Current and next-generation atmospheric neutrino experiments (IceCube, IceCube-Upgrade, Super-K, Super-K-Gd, and KM3nET-ORCA) have comparable or better sensitivity to neutrino oscillation parameters.**
- Beyond determining the oscillation parameters, atmospheric neutrino experiments also **play a significant role in constraining physics Beyond the Standard Model**, e.g., non-standard neutrino interactions, among others.

Super-K
<u>**Already operating in Gd mode**</u>

IceCube and IceCube-Upgrade
<u>**Funded to be deployed in 2025**</u>

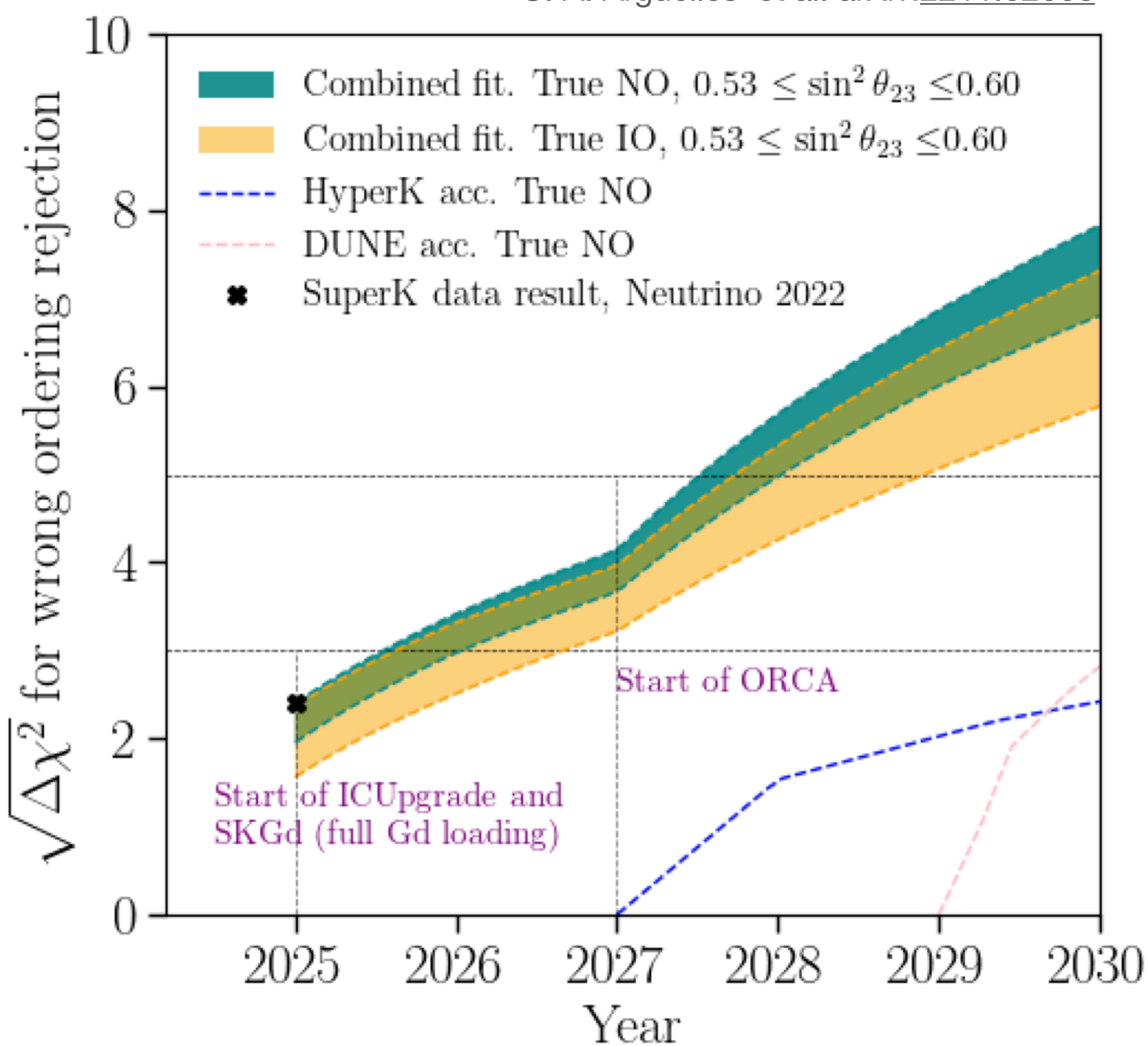


KM3NeT/ORCA
<u>**Under construction, more than 15% built (7,500 PMTs)**</u>



Neutrino Ordering Determination With Atmospherics by 2030 (At the Start of DUNE)

C. A. Argüelles et al. arXiv:2211.02666



Combination of atmospheric experiments will determine the neutrino ordering unambiguously by the end of the decade.

This is without JUNO!

Take Home Message

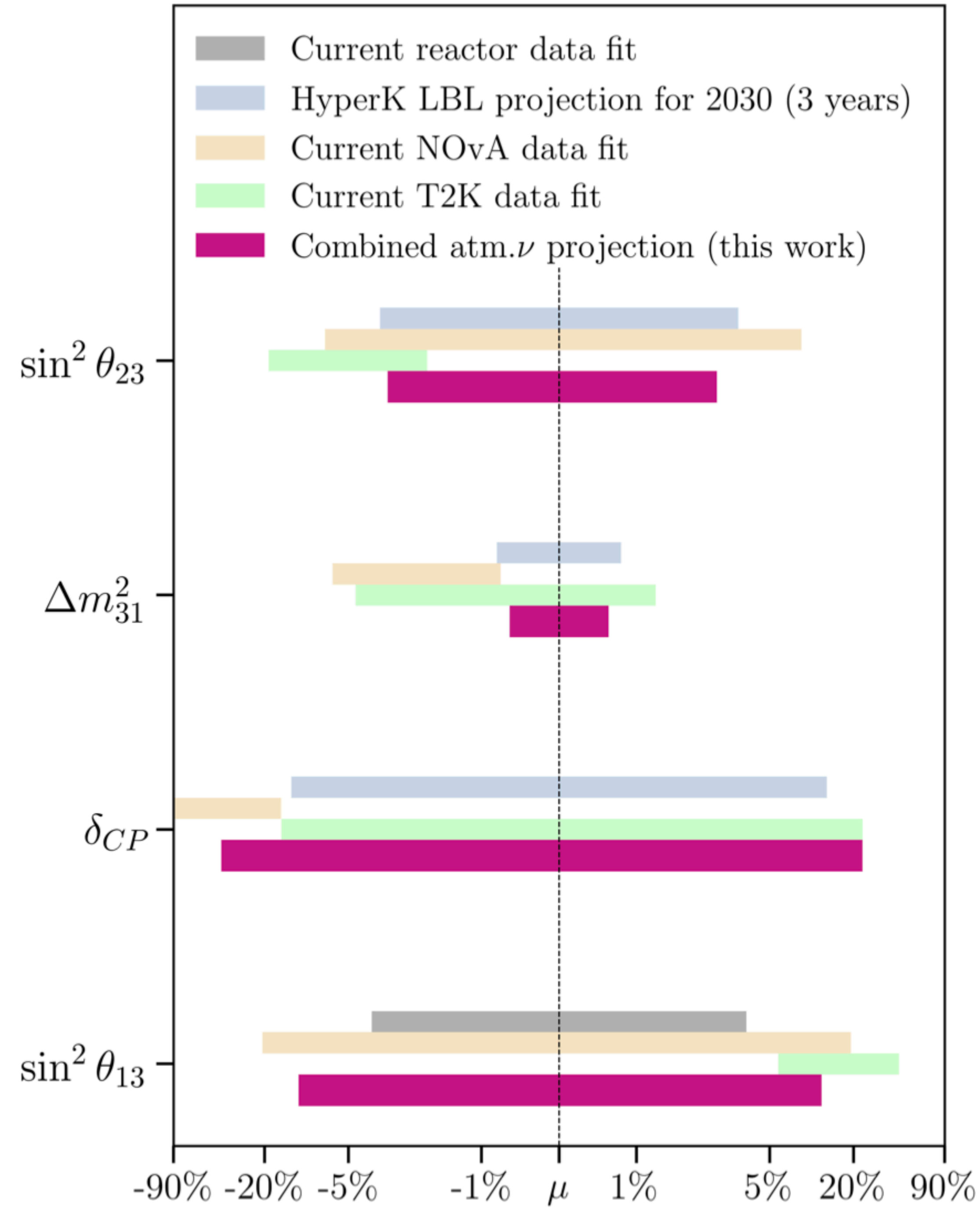
Atmospheric neutrino experiments that will operate this decade will significantly change the landscape of neutrino oscillation measurements by 2030.

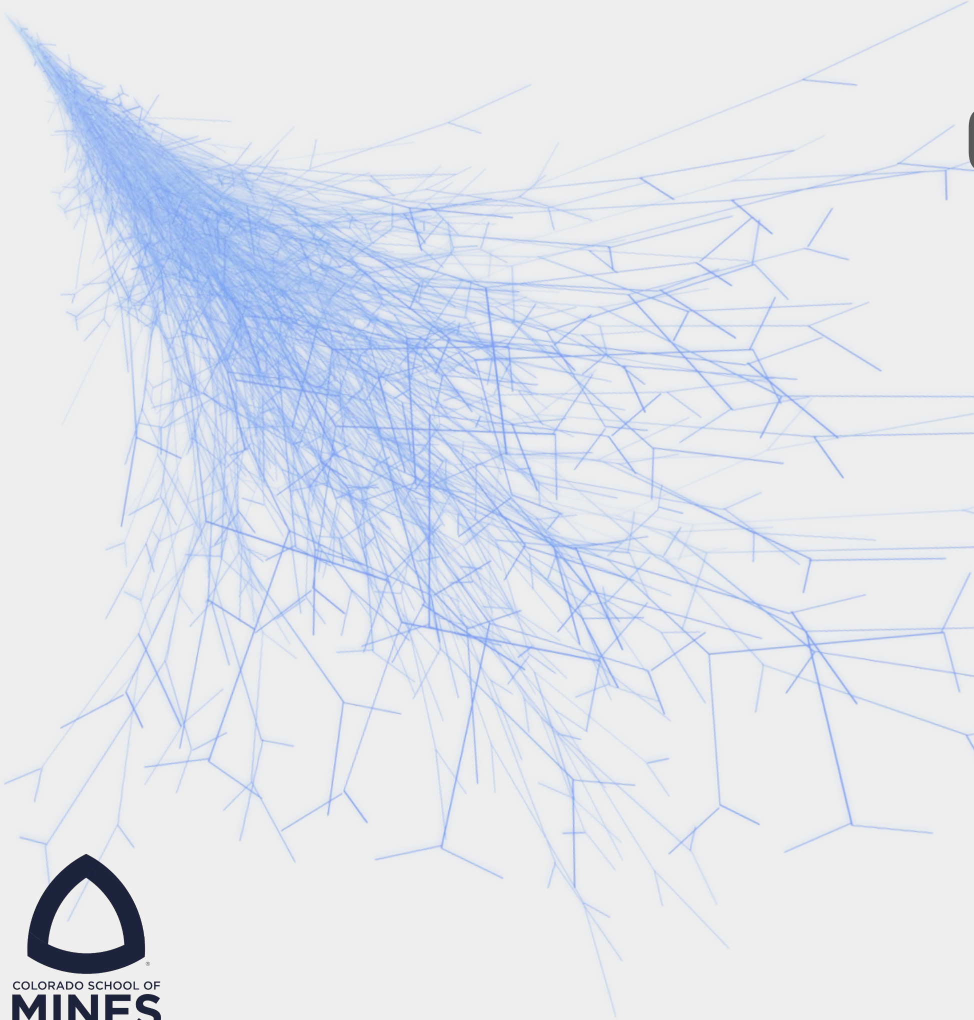
Combination of the experiments capabilities, in particular, SK-Gd, enables access to the CP-phase on an orthogonal data set than long-baseline experiments.

By 2030: Two measurements of CP-phase
- Accelerator: T2K+Nova
- Atmospheric: IceCube + SK + ORCA

Capacities of atmospheric neutrino experiments need to be taken into account when planning next-generation experiments (DUNE, HK, IceCube-Gen2).

C. A. Argüelles et al. arXiv:2211.02666





Comment: The Pierre Auger Observatory and the Telescope Array Project need to be supported into the 2030s.

P5 Town Hall at Fermilab and Argonne
Thursday, March 23rd

Eric Mayotte
for the conveners and contributors of the Snowmass UHECR White Paper*

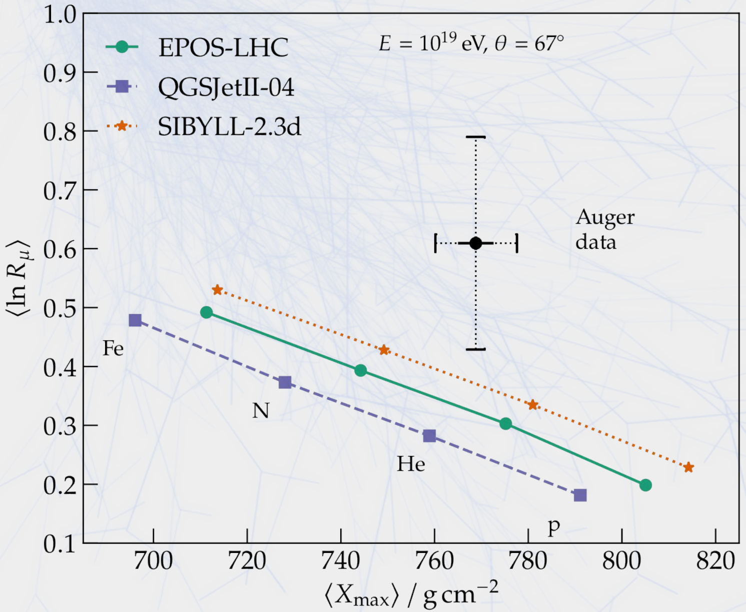
COLORADO SCHOOL OF MINES

*source for all figures

Astropart. Phys. 149 (2023) 102819

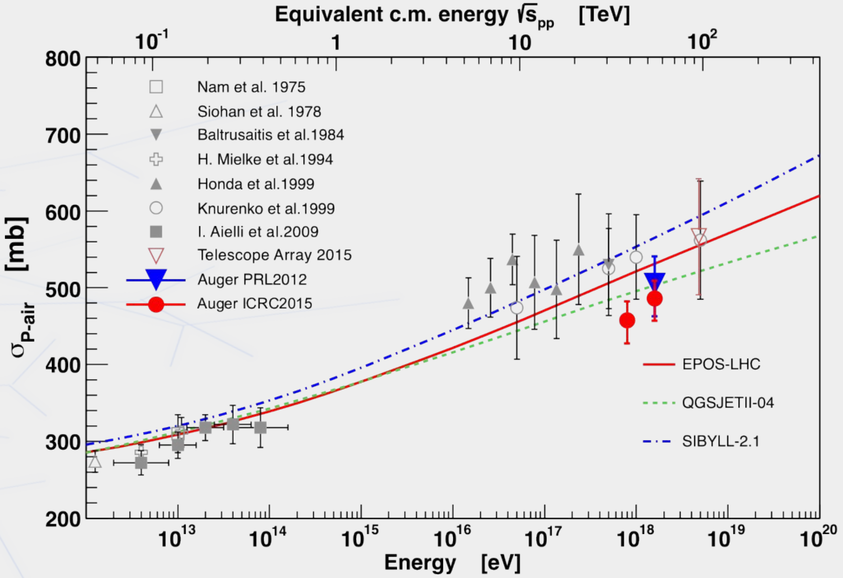
UHECR experiments contribute strongly to high energy physics.

Auger has made highest energy measurement of muon production in hadronic cascades



Significant tension found with the moun production expected from extrapolated LHC-based hadronic interaction models

UHECR experiments have provided the highest energy direct measurements of p-air cross section

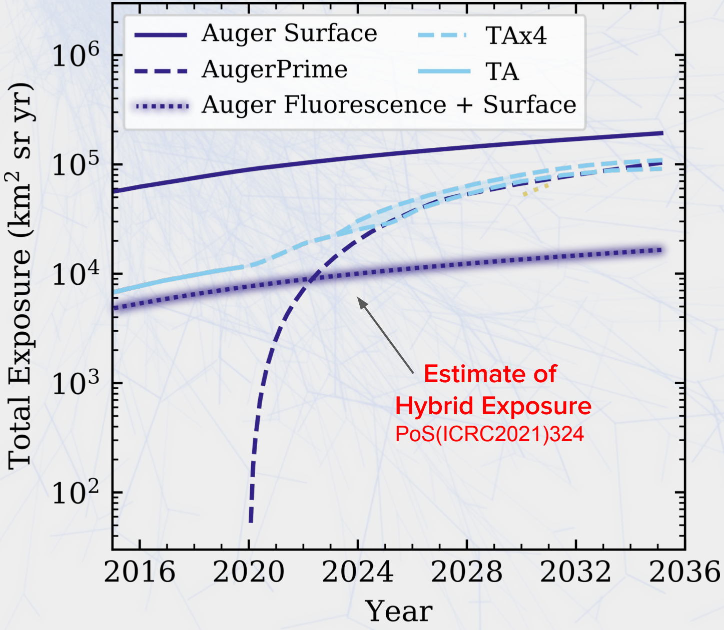


Updated cross sections coming in next year with 2x increase in statistics

➡ Further improvements from upgrades

10-years of data with upgrades will significantly improve measurements.

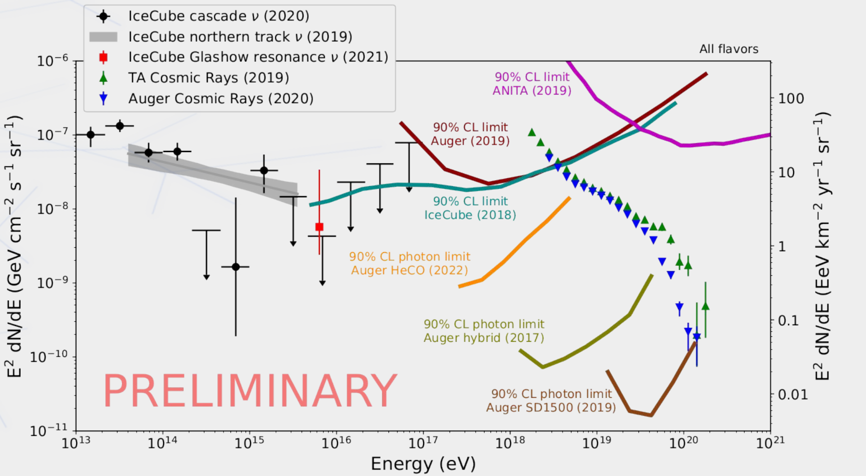
AugerPrime improves shower component sensitivity and will surpass hybrid statistics in next few years



- With 10-years of AugerPrime, statistics for μ-production and $\sigma_{p\text{-}air}$ measurements ~10x higher
- TA $\sigma_{p\text{-}air}$ measurement statistics ~5-10x higher

UHECR observatories are Multi-messenger observatories.

Auger has UHE neutrino exposure matching IceCube and currently world leading UHE photon exposure

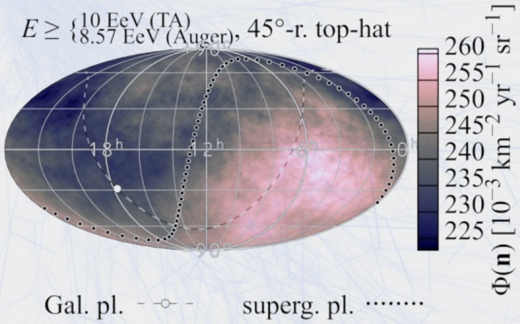


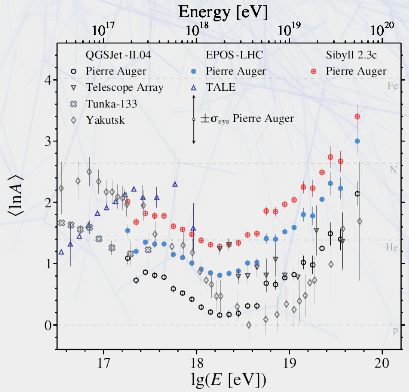
Exposures begin exceeding expected flux in many acceleration scenarios and sensitivities are improving

➡ First observations hoped for soon!

Preparing for the next generation

Upgrades will further understanding of UHECR Mass composition and anisotropies



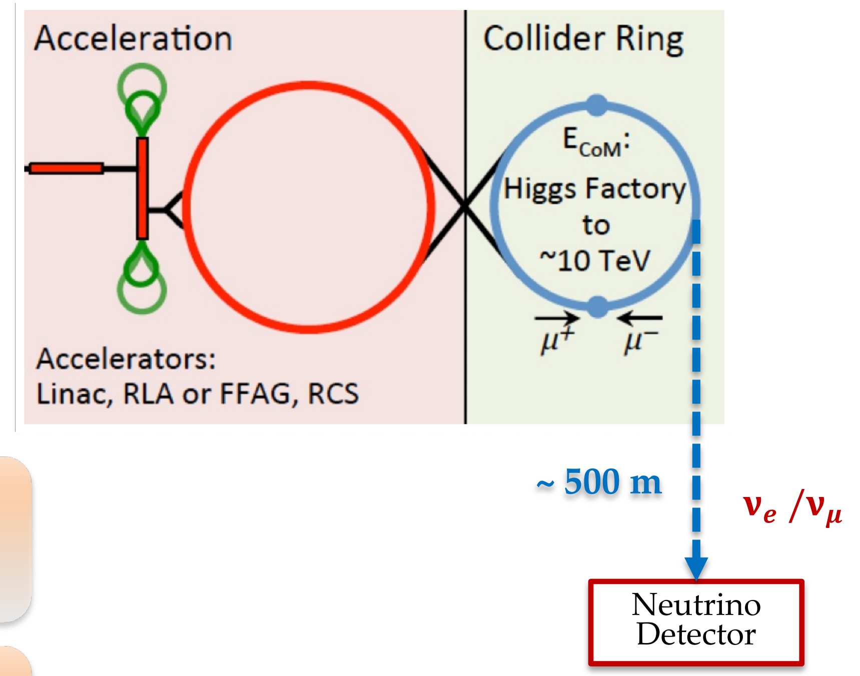


Constraints on mass composition at highest energies critical to design of next generation

- **R&D activities for GCOS, GRAND and POEMMA already planned or underway at Auger/TA**
- **Simultaneous Auger/TA data-taking highly desired for GRAND, GCOS, POEMMA and IceCube-Gen2 ➡ Next-Gen data-taking not until 2030s**

Experiment	Timeline
Pierre Auger Observatory	AugerPrime upgrade
Telescope Array (TA)	TAx4 upgrade
IceCube / IceCube-Gen2	Upgrade + surface enhancement → IceCube-Gen2 deployment → IceCube-Gen2 operation
GRAND	GRANDProto 300 → GRAND 10k → GRAND 200k multiple sites, step by step
POEMMA	EUSO program → POEMMA
GCOS	GCOS R&D + first site → GCOS further sites
	2025 2030 2035 2040

Neutrino Fixed Target Experiment at a Muon Collider



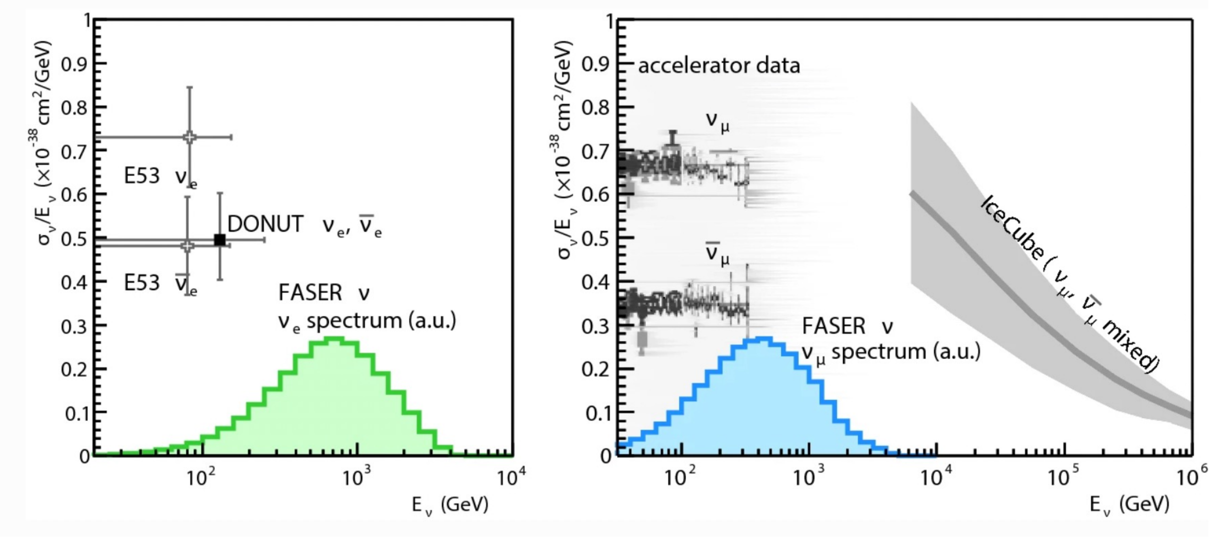
Why would a Muon Collider Help?

- Very high beam luminosity
- Precisely known energy spectra
- Equal numbers of e/μ (anti)neutrinos
- Very well determined beam intensity

- Ideal to investigate rare/new neutrino interactions
- Search for BSM physics

Case 1: SM Search (Precision in Neutrino Cross Section Measurements)

FASER Collaboration, 2020



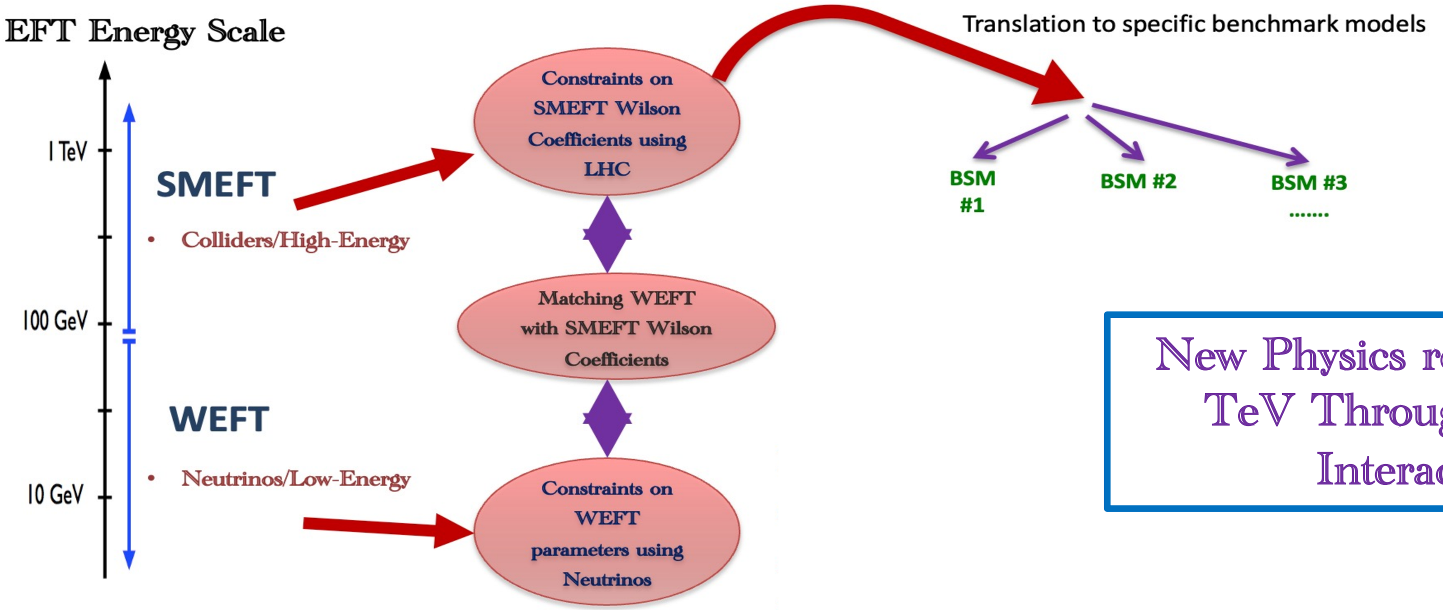
- ❑ Currently no high energy ν_e beam
- ❑ A lot of ν_μ, but not well known beam

- Well known beam, direct extraction of the x-sections with much greater precision
- DIS dominates, we can probe nucleon structure at low Bjorken x and high Q^2

Also, running of the weak mixing angle, etc…

Case 2: Indirect New Physics Search (SMEFT)

Falkowski, González-Alonso, Kopp, Soreq, *ZT*, JHEP (2021)



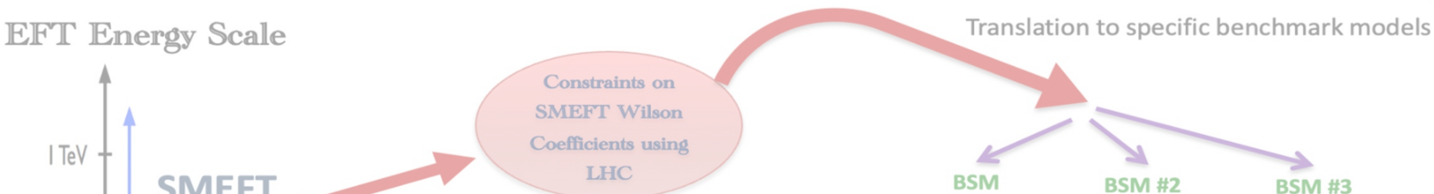
New Physics reach of tens of TeV Through Neutrino Interactions?

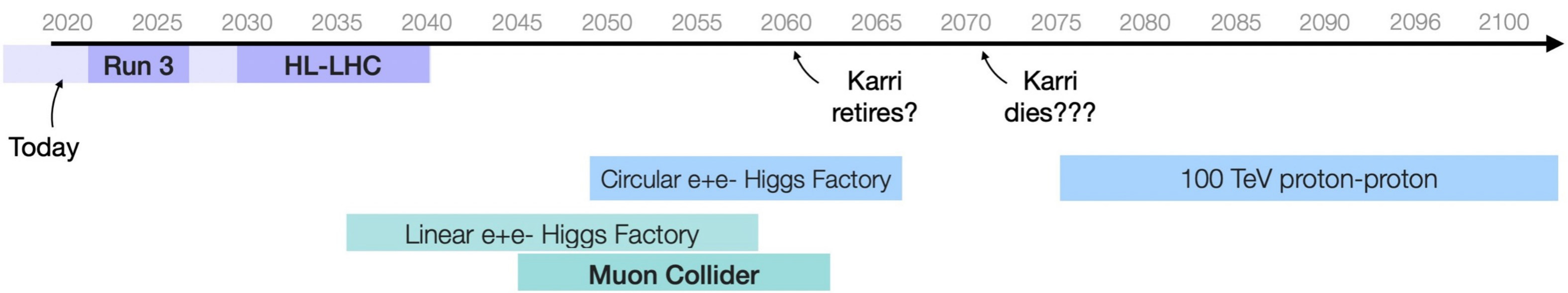
Using neutrinos at a muon collider we can:

- Do precision measurements of neutrino interactions (DIS x-section, weak mixing angle, etc.)
- Probe very heavy particles by precisely measuring low-energy observables using the EFT formalism.
- Unlike other probes (ATLAS and CMS, etc.), a neutrino detector has the unique capability to identify the neutrino flavor. This is crucial complementary information in case excesses are found elsewhere in the future.
- We are NOT yet prepared to identify all the interesting things we can do!

Case 2: Indirect New Physics Search (SMEFT)

Falkowski, González-Alonso, Kopp, Soreq, ZT, JHEP (2021)





From Karri Folan DiPetrillo

Give early career physicists the opportunity to make a 10 TeV Muon Collider a reality

Modest ask: support R&D and design development so we can make the big ask at the next P5 with progress in hand

Us…

- Do precision measurements of neutrino interactions (DIS x-section, weak mixing angle, etc.)
- Probe very heavy particles by precisely measuring low-energy observables using the EFT formalism.
- Unlike other probes (ATLAS and CMS, etc.), a neutrino detector has the unique capability to identify the neutrino flavor. This is crucial complementary information in case excesses are found elsewhere in the future.
- We are NOT yet prepared to identify all the interesting things we can do!

WIMPs are Not Dead

Andrea Albert (Los Alamos National Lab)
P5 Townhall
3/23/23

LA-UR-23-22862

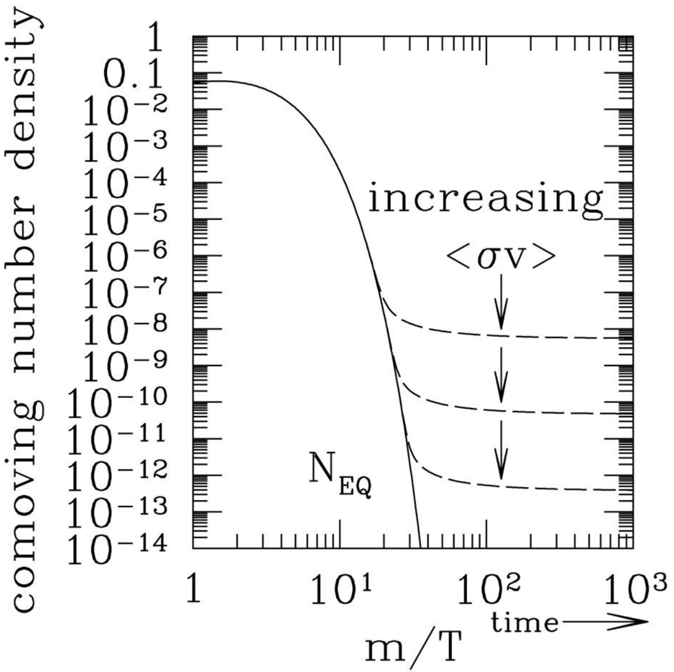
WIMP Dark Matter

- Weakly Interacting Massive Particle (WIMP)
  - 5 GeV - 100 TeV mass scale

- A thermally-coupled ~100 GeV particle in the early Universe with weak scale $\boldsymbol{\sigma}_{ann}$ independently produces the observed dark matter abundance today measured by the CMB

- Several WIMP candidates from independently motivated theories like SUSY

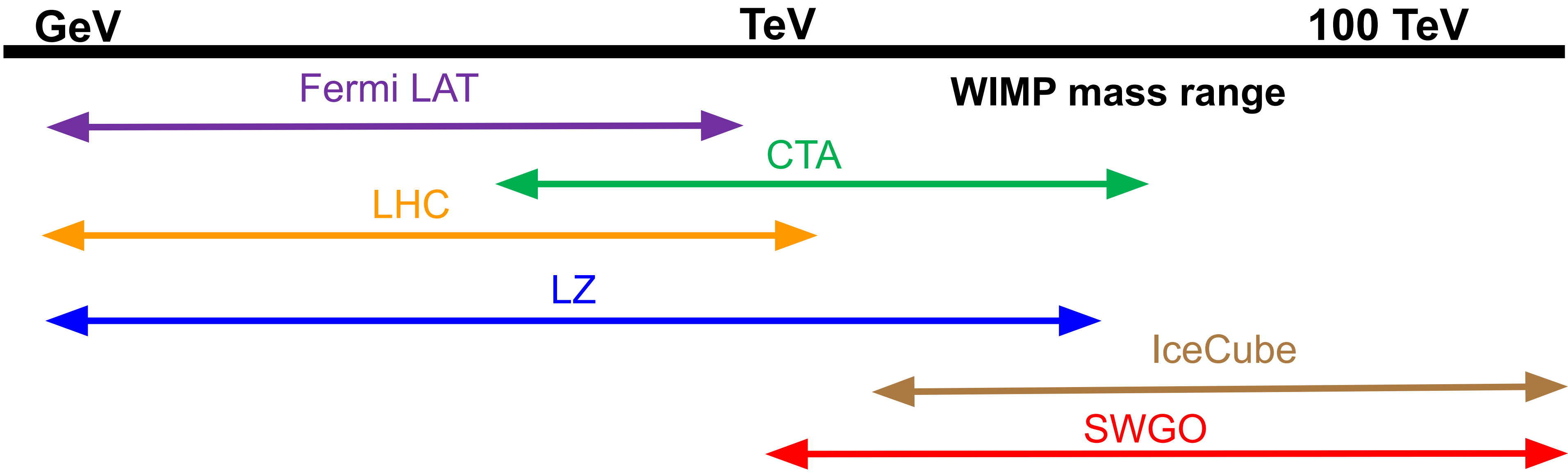
- Thermal WIMPs aren't the only dark matter candidates, but are a **well-motivated hypothesis we must test!**
  - We have only just begun to probe WIMP phase space



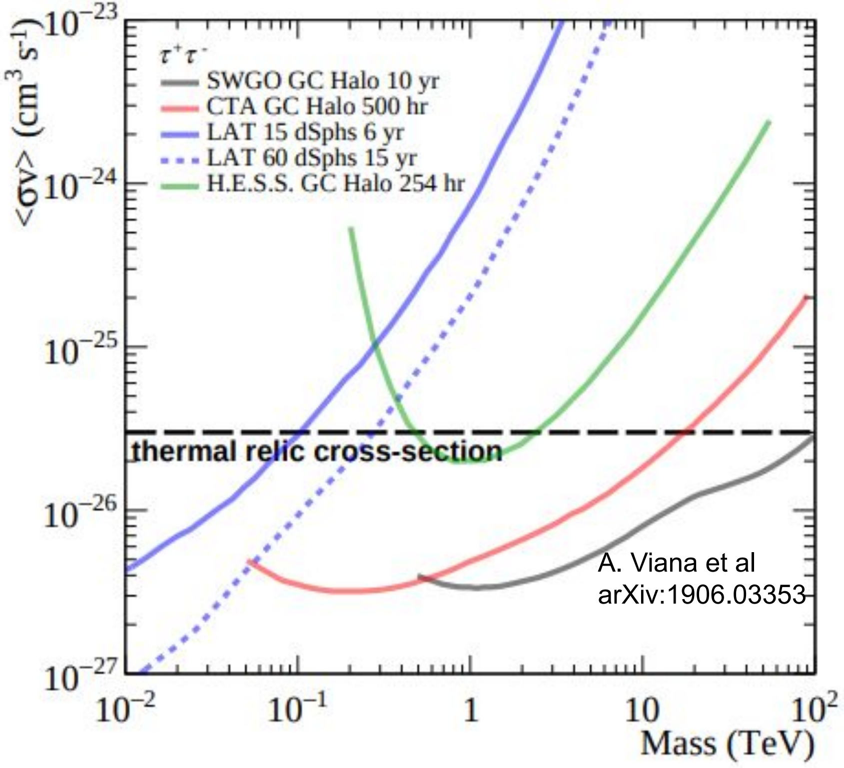
E. Kolb and M. Turner, *The Early Universe*, Westview Press (1994)

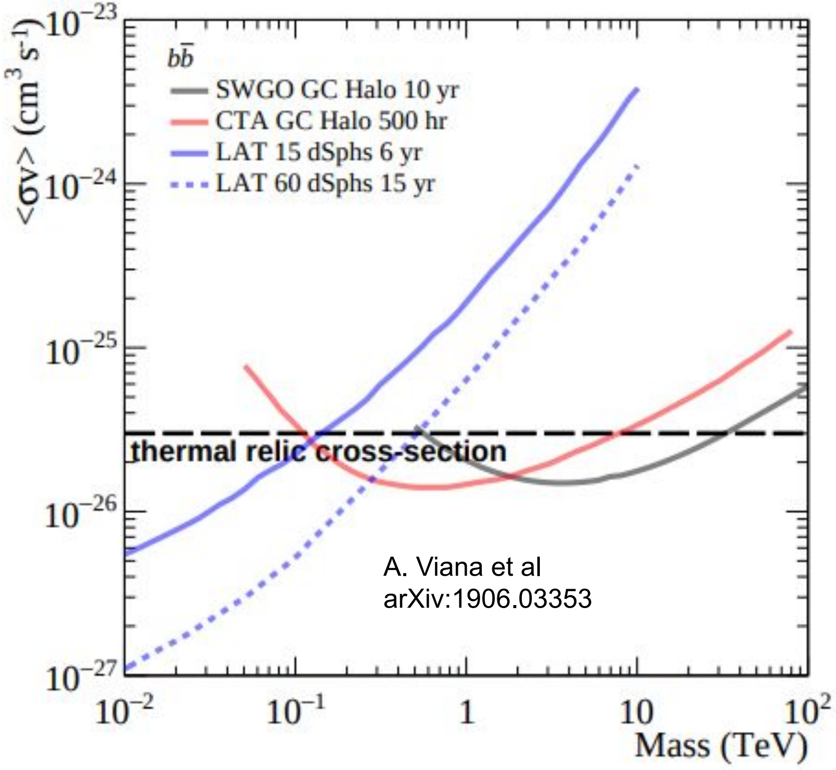
- Diverse experimental portfolio is needed to cover all of the thermal WIMP mass range
  - This includes small and mid-scale experiments

- Direct detection (e.g. LZ), indirect detection (e.g. SWGO), and collider production (e.g. LHC) are *all needed* to probe the full mass range and various particle interaction channels



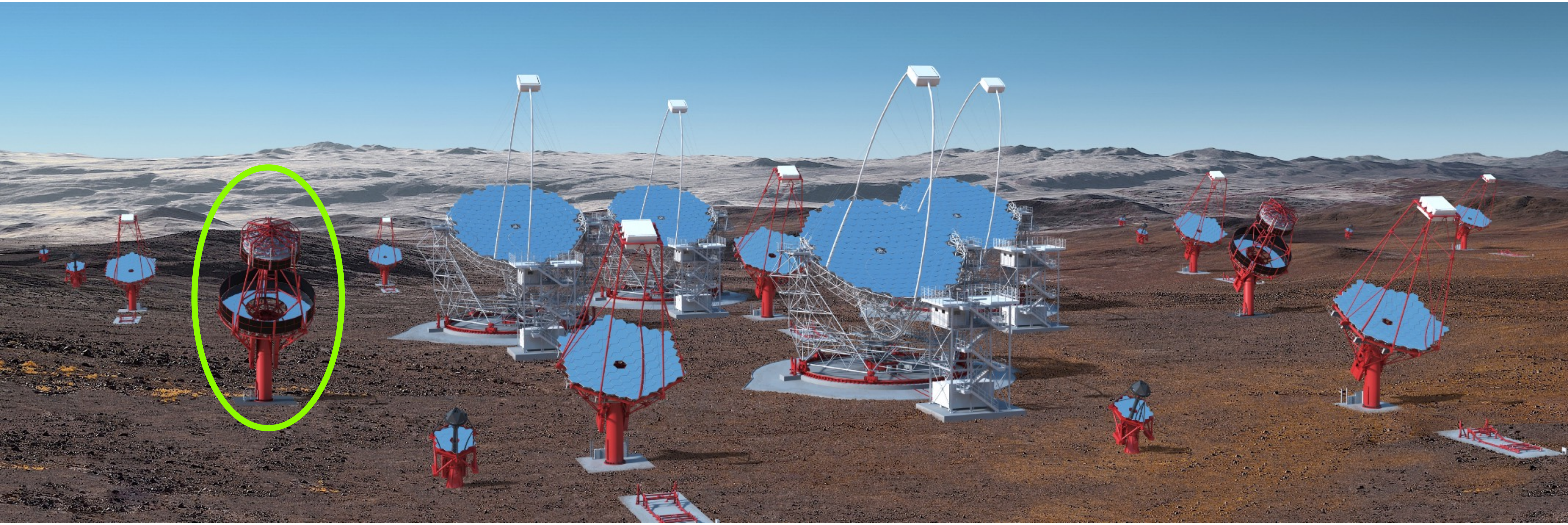
For example, future indirect detection of cosmic gamma rays is expected to probe the entire thermal WIMP mass range with continued observations with the Fermi LAT, and the next generation gamma-ray observatories CTA and SWGO





CTA: The Cherenkov Telescope Array

Gamma rays from the universe → fundamental physics and cosmology

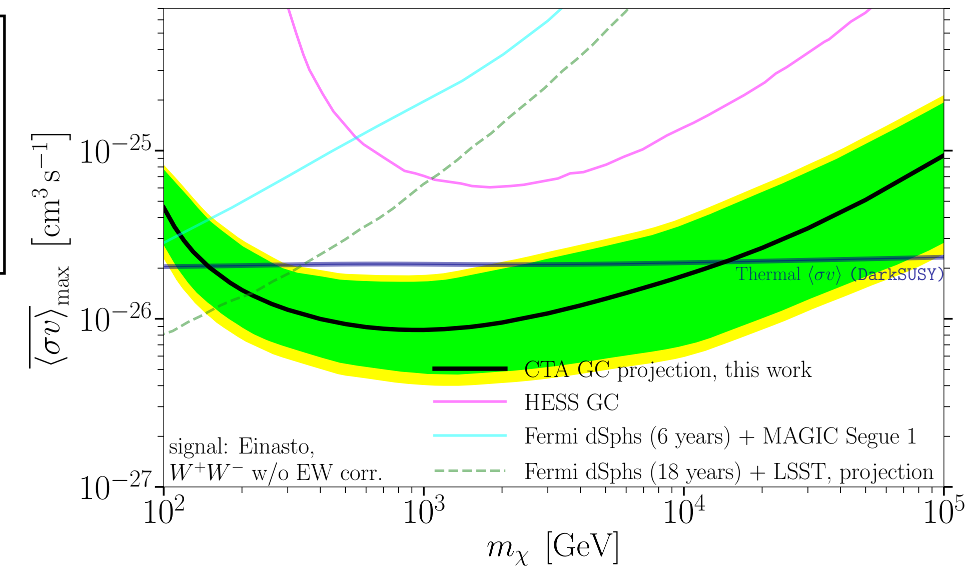


- Dark Matter
- Axion-Like Particles
- Primordial Black Holes
- Lorentz Invariance Violation
- Cosmic IR/Optical Background
- Intergalactic Magnetic Field

CTA dark matter: arXiv: 2007.16129

CTA fundamental physics and cosmology: arXiv: 2010.01349

Justin's Talk about CTA at P5

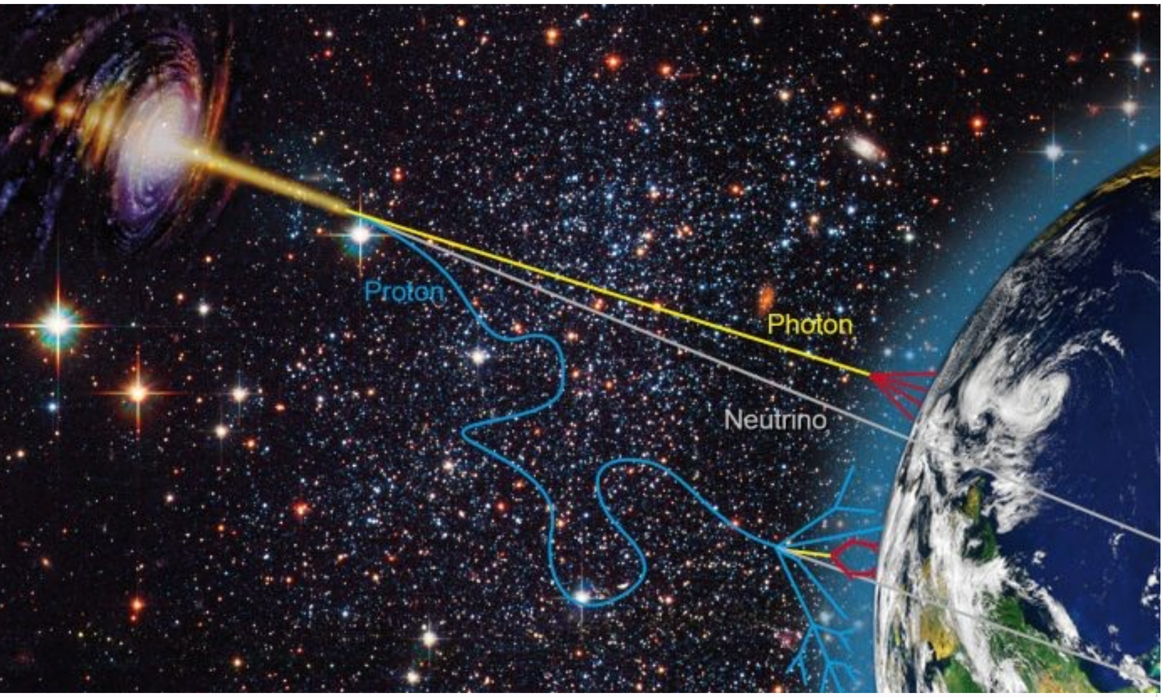


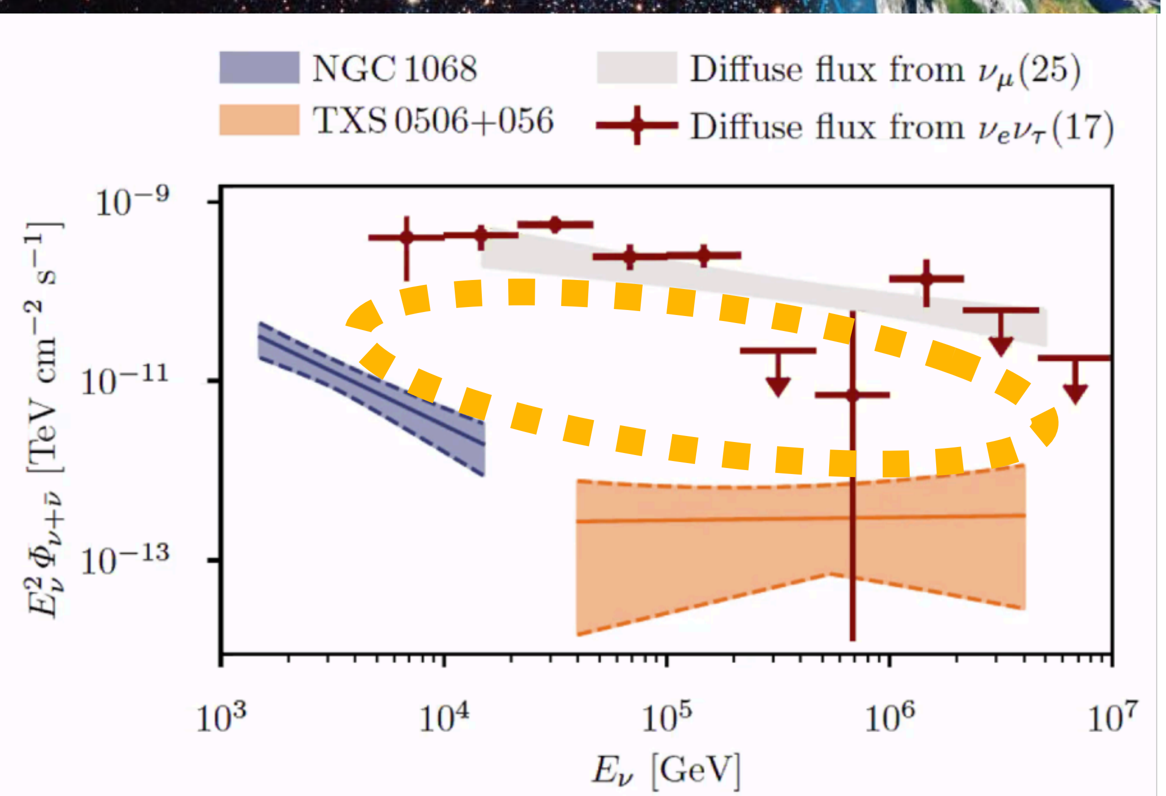
Qi Feng for the CTA SCT Project, Snowmass P5, 2023 March 23

With support from:

CTA & IceCube (Gen2)

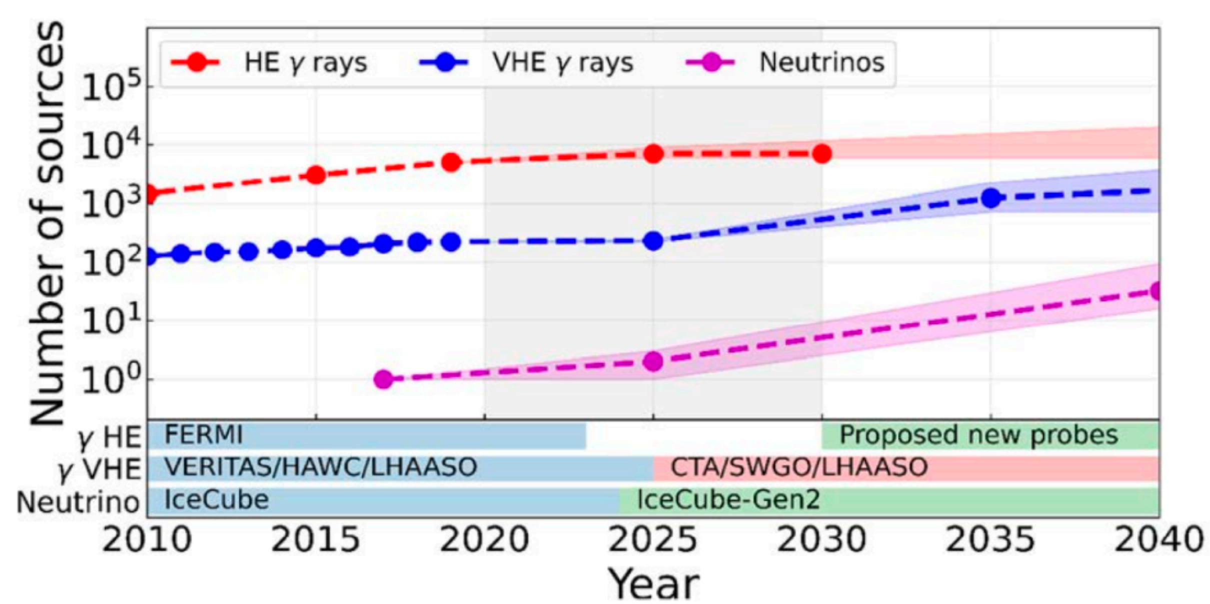
the prospects of multi-messenger astrophysics with next-generation gamma-ray and neutrino observatories





- Neutral messengers for extreme cosmic accelerators.
- Gamma rays must be produced together with neutrinos.
- The brightest neutrino sources ≠ the brightest gamma-ray sources
  - Need to understand the extreme environments in sources.

CTA uniqueness: Transient discovery potential, angular resolution, energy coverage/resolution.



Qi Feng for the CTA SCT Project, Snowmass P5, 2023 March 23

With support from:

The Importance of Small Experiments for the Vitality of Neutrino Physics

Cristian Roca Catala - P5 Town Hall @ Fermilab & Argonne
Thursday - 28.III.2023

What constitutes a "small experiment"?

- Projects below the $10M funding scale
- Not connected to a dedicated facility - large scale project
- More focused on innovation, research and development

Benefits

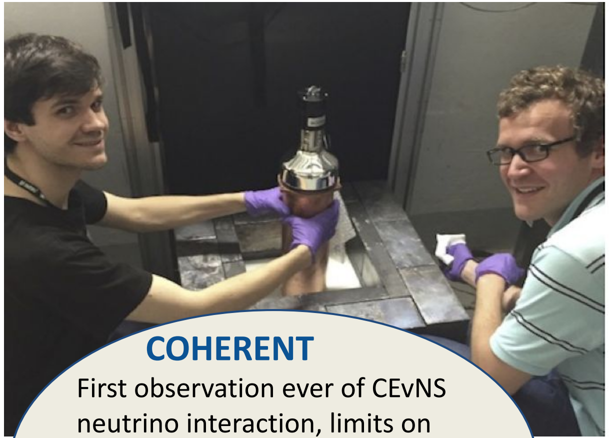
- **Training**: opportunity for **student**/early career folks to get **involved** during planning and execution of ideas
- **Leveraging**: existing equipment and **infrastructure** at Uni and Labs can be **repurposed**/reutilized
- **Exploration**: cover a wide net of **diverse** research ideas that bigger projects rarely develop
- **Incubation**: can become **foundational** stones for future larger projects, **future** thinking.
- **Efficiency**: science gets generally done within **quicker** timeframes with **smoother** output
- **Flexibility**: small scale allows for **nimble** reaction to emerging **opportunities**

Examples of small experiment success

(just a small subsample!)

PROSPECT & CHANDLER

First surface detection of Rx neutrino, addressed spectrum and rate anomalies



COHERENT

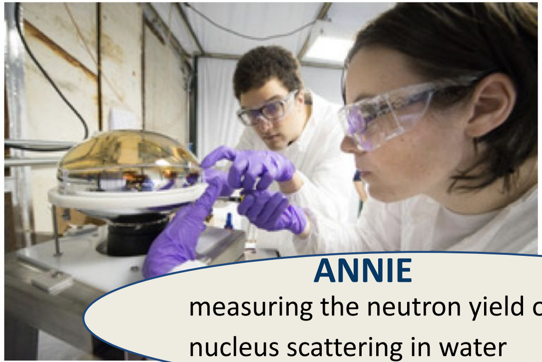
First observation ever of CEvNS neutrino interaction, limits on BSM physics

CONNIE & MINER

hunting for low-threshold CEvNS with different innovative techs

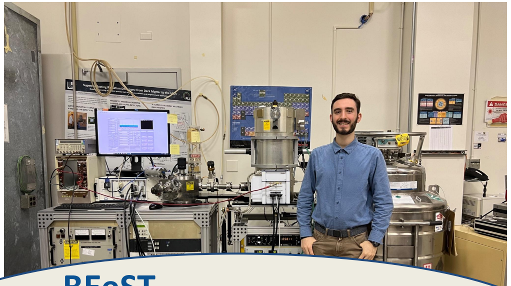
NUCLEUS

Sterile neutrino searches, reactor nu CEvNS, BSM



ANNIE

measuring the neutron yield of neutrino nucleus scattering in water



BEeST

looking for sterile neutrino in sub-MeV range, developing superconducting sensors

How to make it better

Challenges

- **Marketing**: research **impact** can be hard to **quantify**, experimental nature can't always be easily justified
- **Management**: larger relative costs of **engineering**, safety approvals, project **management**
- **Community**: smaller scale usually means **weaker**, less unified **voice**

- **Deprioritization**: **funding** focus on larger experiments might place extreme **pressure** on small and mid scale projects

Support

- **Consistent Funding**: dedicated **predictable FOA** for small scale
- **Diverse Funding**: **support** targeted for **non-HEP** host Unis and Labs
- **Management Resources**: community **resource pool** for engineering, H&S, project management expertise

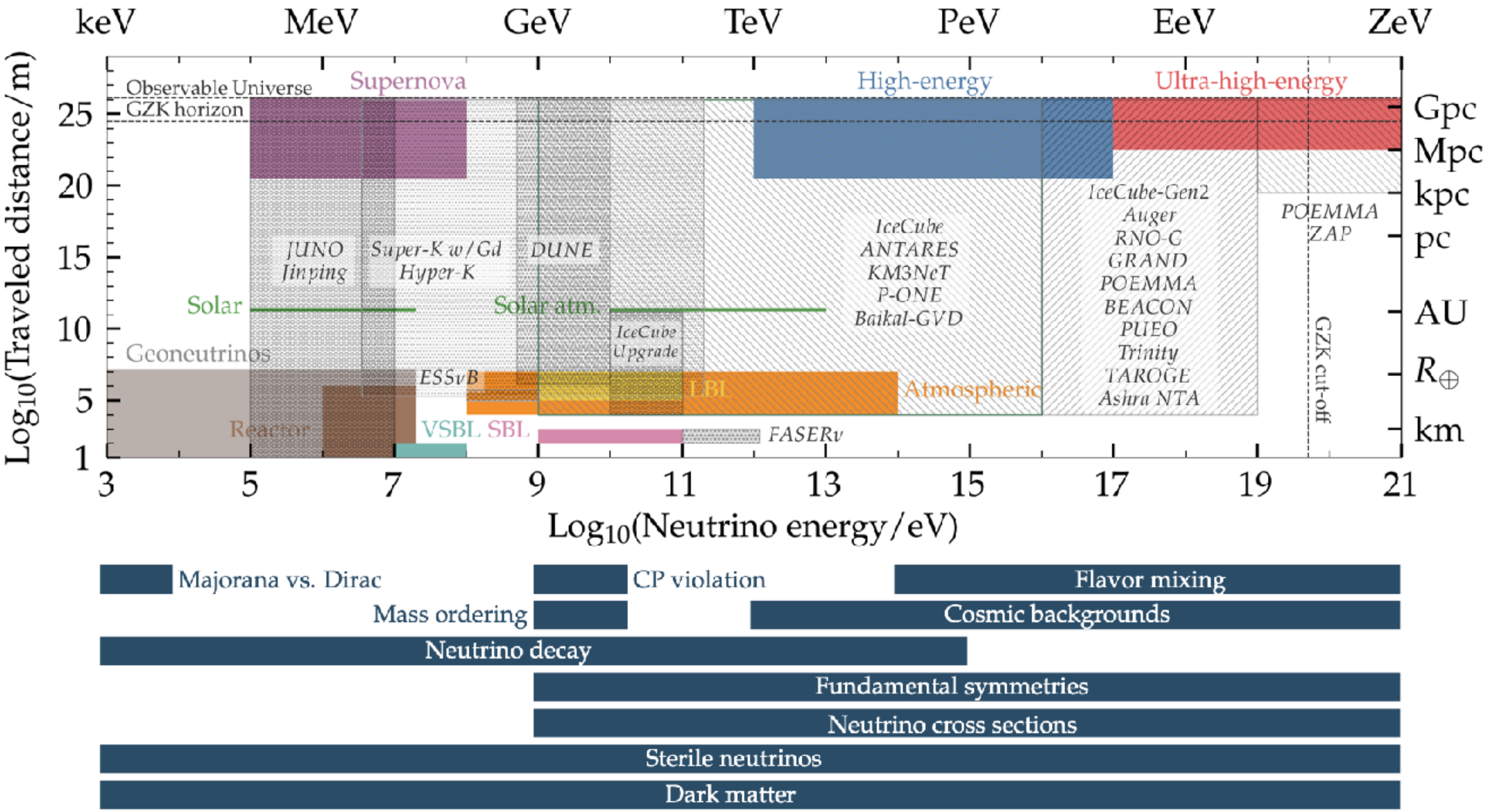
Thanks for your attention!

This work has been performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC.
LLNL-PRES-XXXXX

Particle Physics with Neutrinos at Ultra High Energies

Stephanie Wissel, Penn State, wissel@psu.edu

- Fundamental physics probe at the **highest energy scales (TeV to ZeV)**
- **Longest baselines** (~Gpc) allow even small effects to accumulate over **cosmological distances**

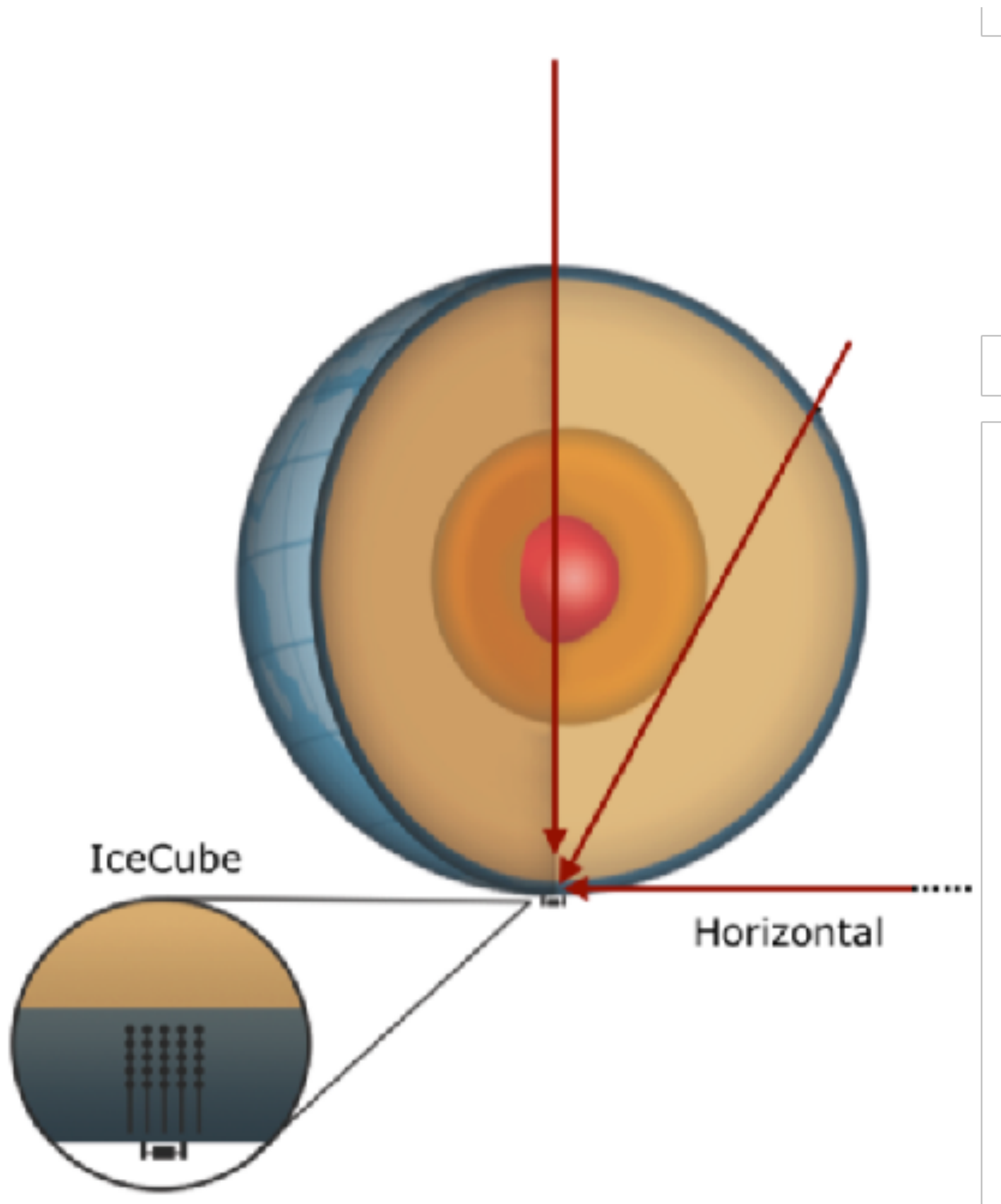


CF7 Topical Report Snowmass

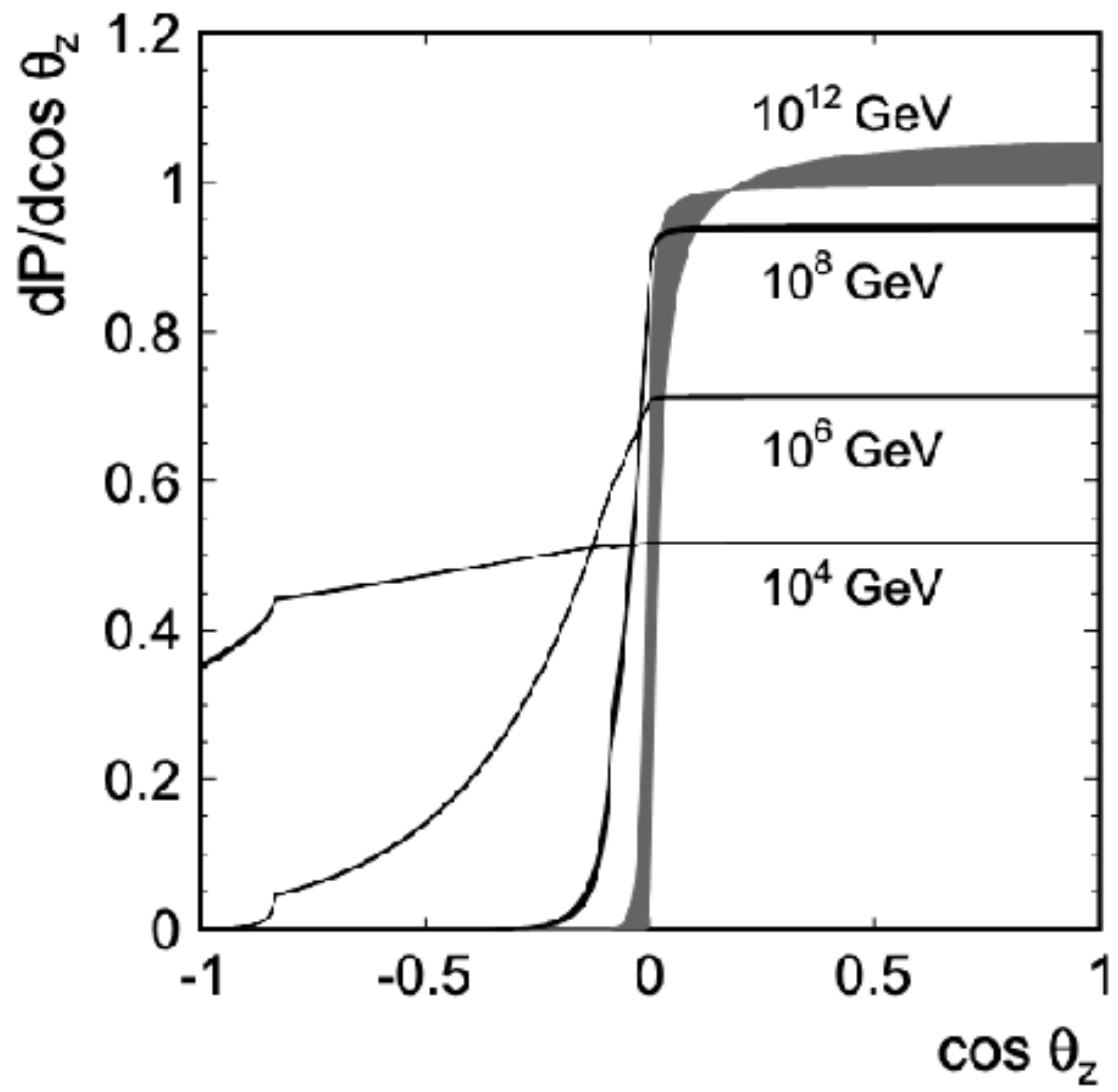
Astro2020 1903.04333

Cross Sections in a New Energy Regime

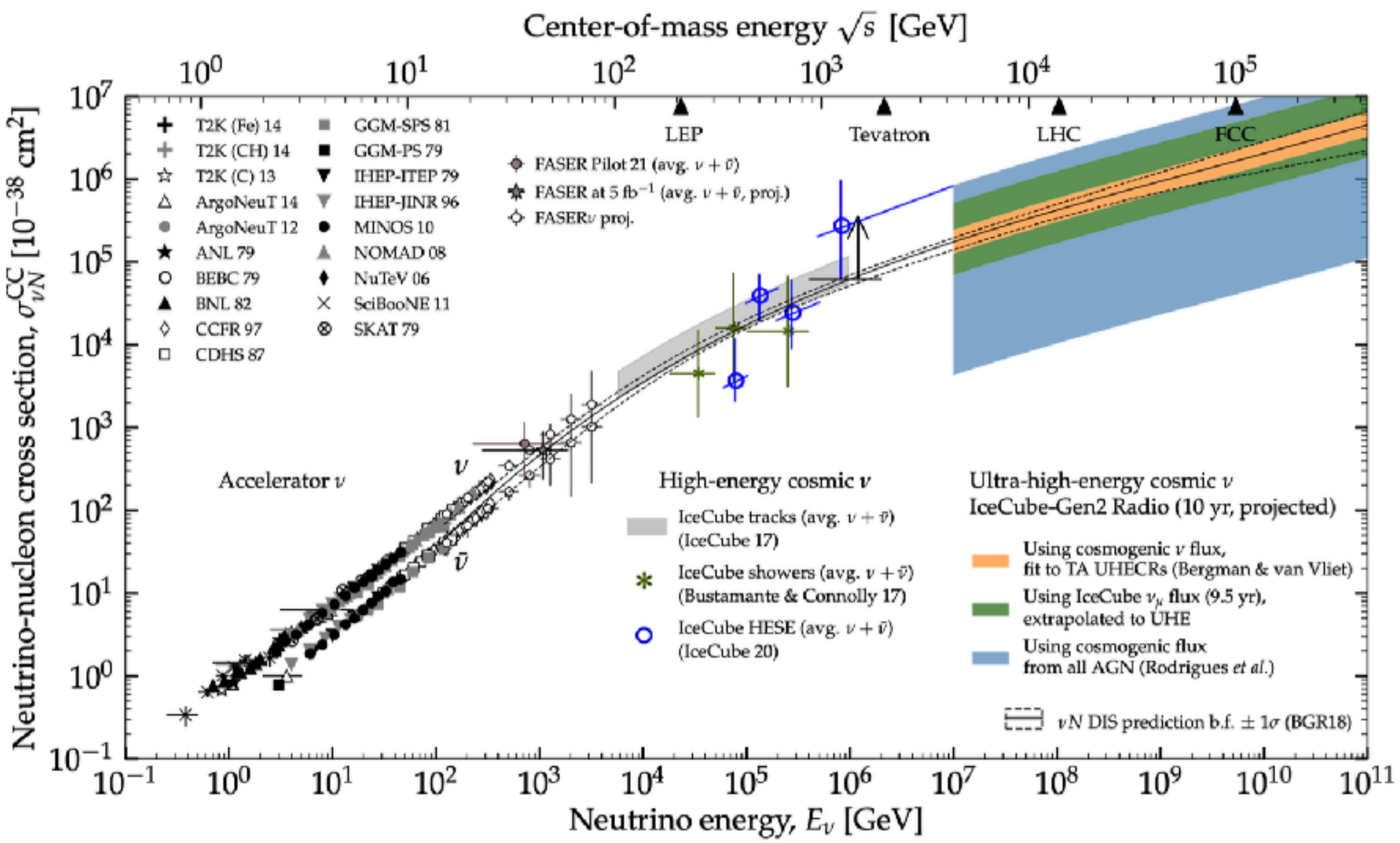
- Probe neutrino interactions previously unmeasured
  DIS cross sections & inelasticity that probe parton distribution functions (low Bjorken-x, high Q^2)
- Ultra-high energies (>100 PeV) will probe new, otherwise unexplorable energy regime ($\sqrt{s} > 30$ TeV)
  Good (zenith) angular resolution over broad energy range (large neutrino target) needed



IceCube 2011



Connolly et al 2011



CF7 Topical Report
Snowmass 21 white paper: 2203.08096

$L_{int} \sim 300$ km: Use Earth-shielding as cross-section analyzer

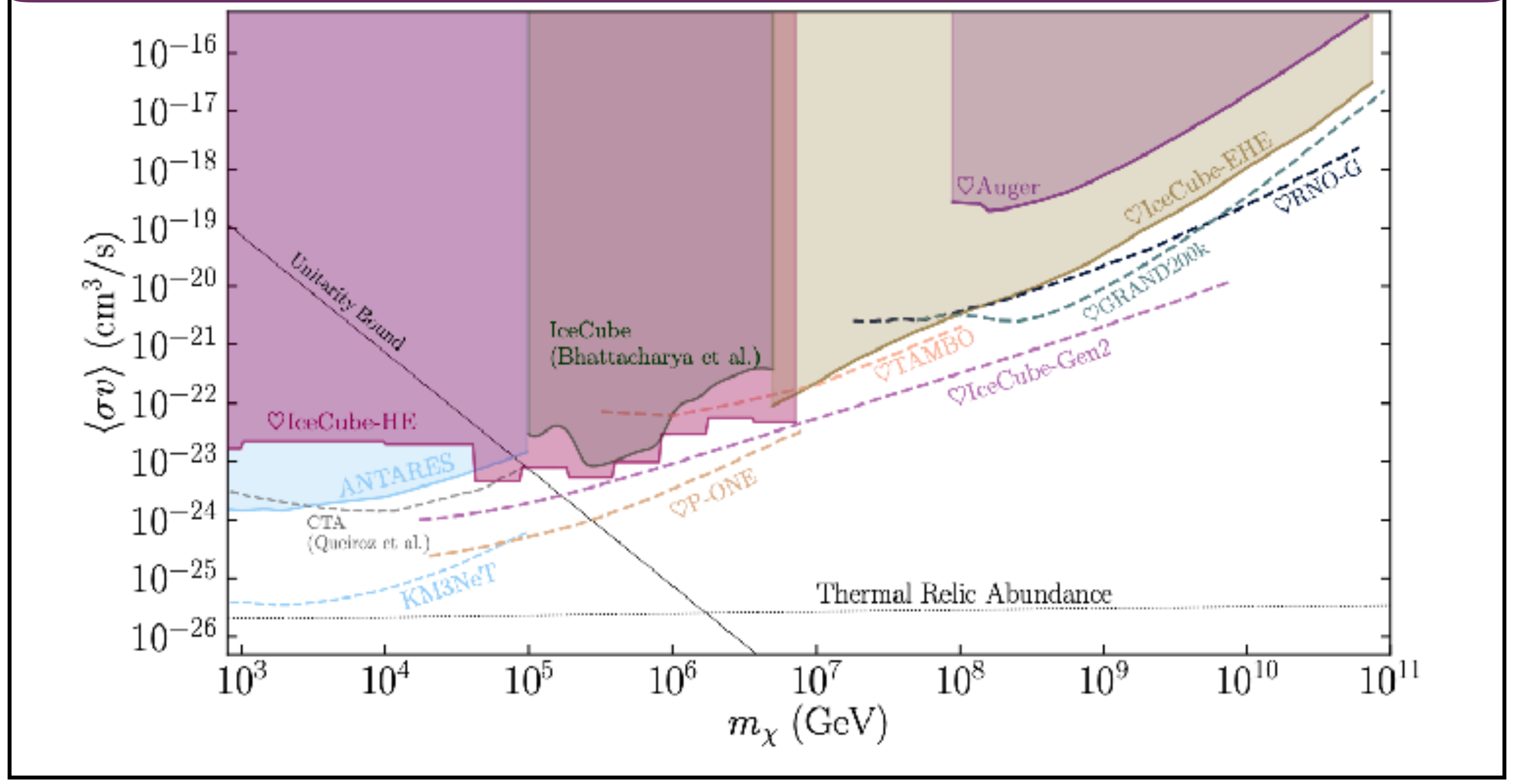
NEW PHYSICS IMPACT ON NEUTRINOS

Palomares-Ruiz, Salvadó arXiv:1907.08690

Argüelles, et al arXiv:1912.09486

Snowmass 21 white paper: 2203.08096

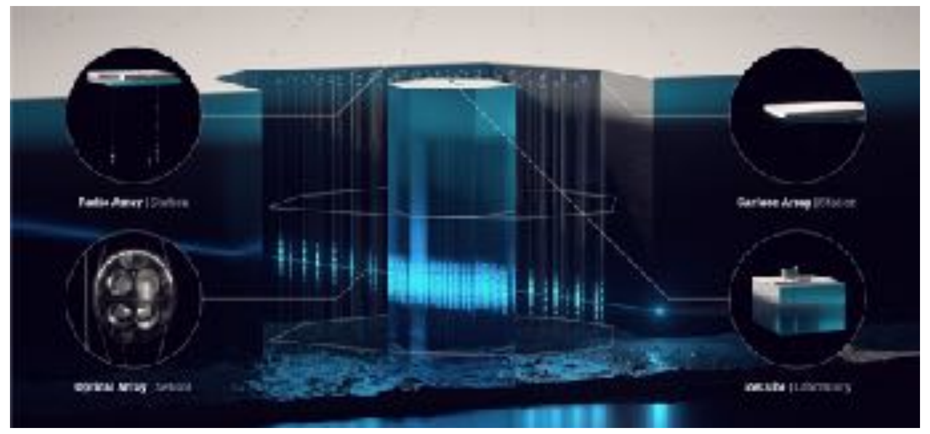
Example:
Super Heavy Dark Matter

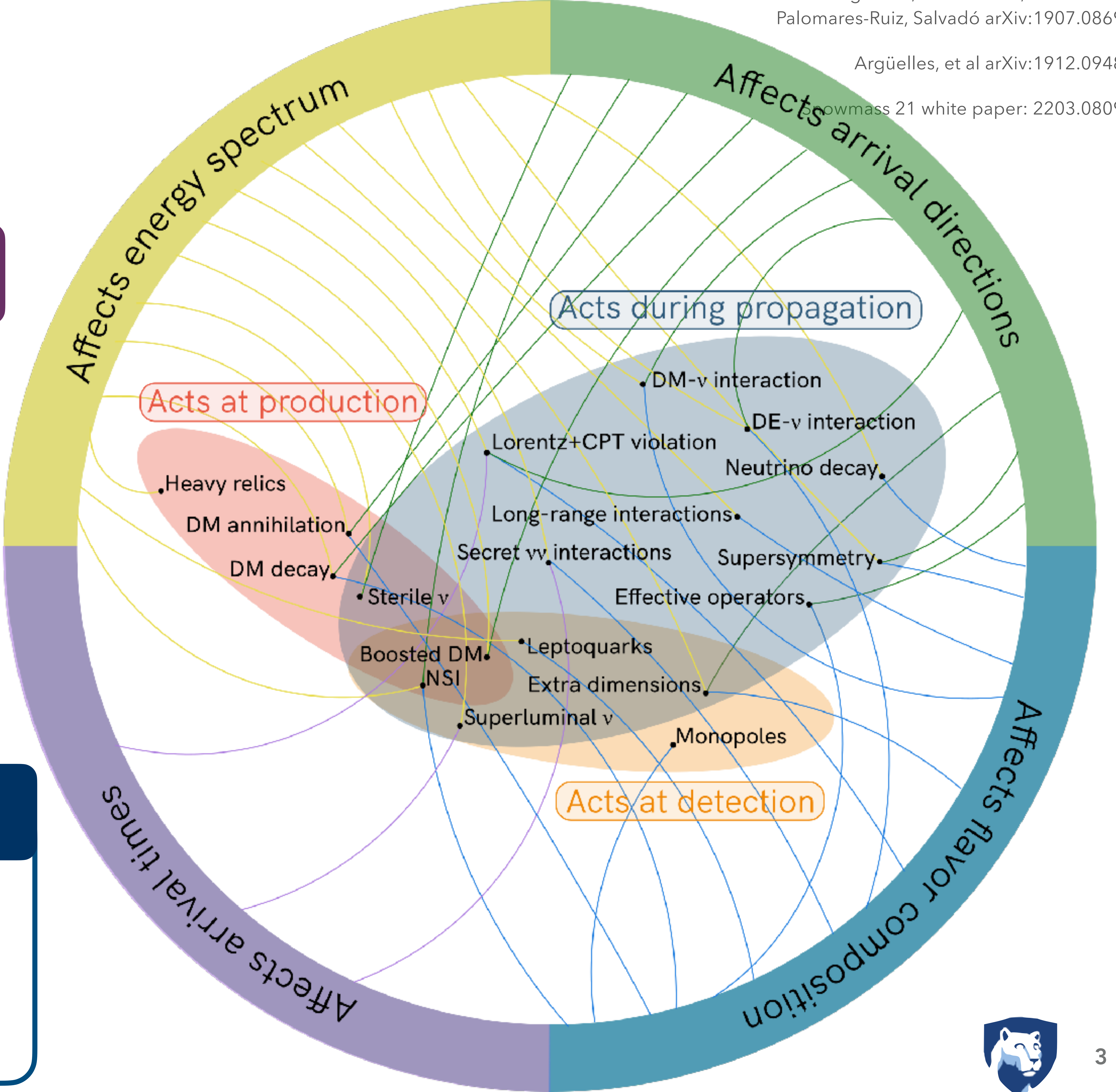


Comprehensive Approach

Broad energy range, multiple techniques, flavor sensitivity

IceCube-Gen2





The PROSPECT reactor antineutrino Experiment: Highlights and future opportunities

Diego Venegas Vargas

The University of Tennessee Knoxville

On behalf of the PROSPECT collaboration

March 23rd – P5 Town Hall at Fermilab and Argonne, 2023

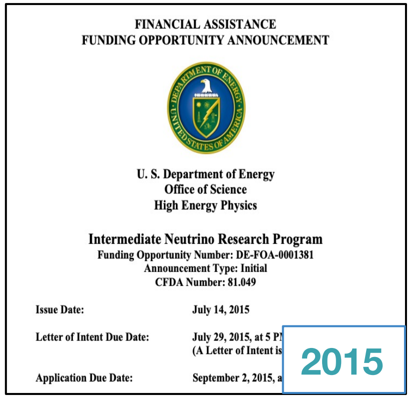
Physics Division

PROSPECT is a successful outcome of the last Snowmass / P5 cycle

Recommendation 4: Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale projects.

Recommendation 6: In addition to reaping timely science from projects, the research program should provide the flexibility to support new ideas and developments.

Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.


FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy
Office of Science
High Energy Physics

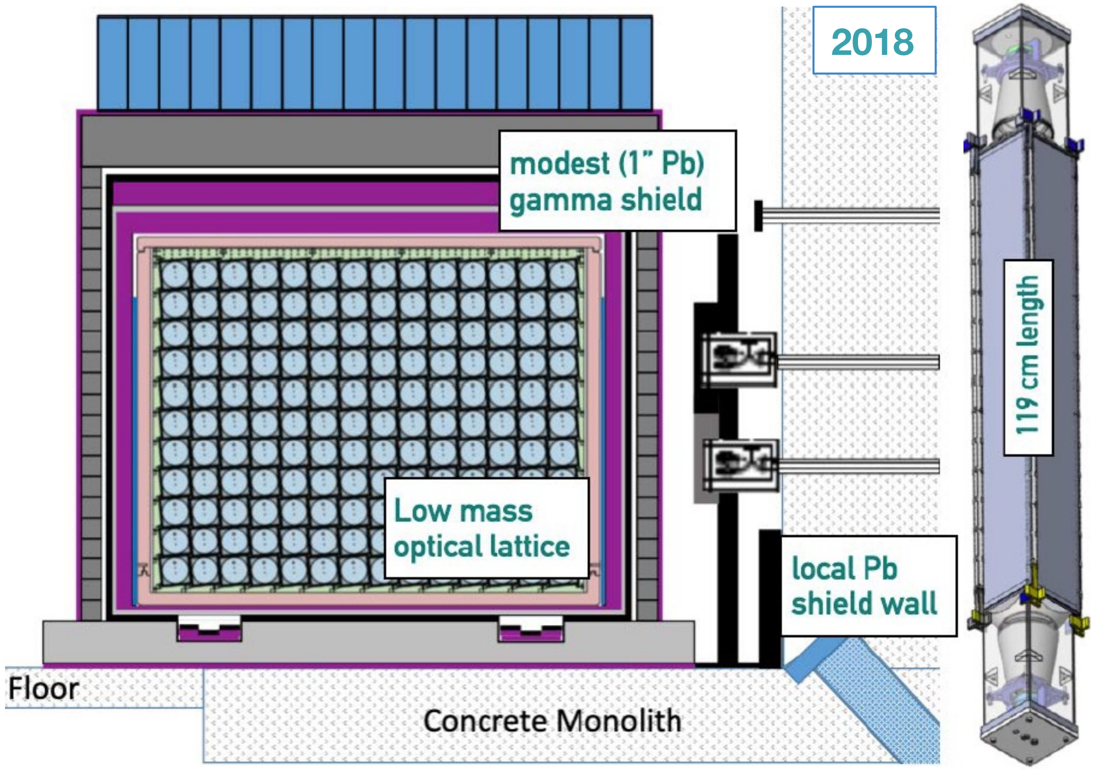
Intermediate Neutrino Research Program
Funding Opportunity Number: DE-FOA-0001381
Announcement Type: Initial
CFDA Number: 81.049

Issue Date: July 14, 2015

Letter of Intent Due Date: July 29, 2015, at 5 P…
(A Letter of Intent is…

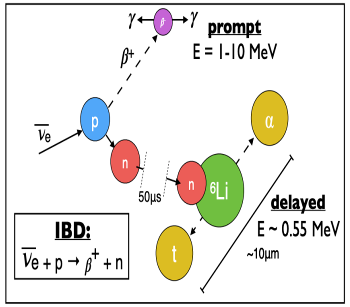
Application Due Date: September 2, 2015, a…

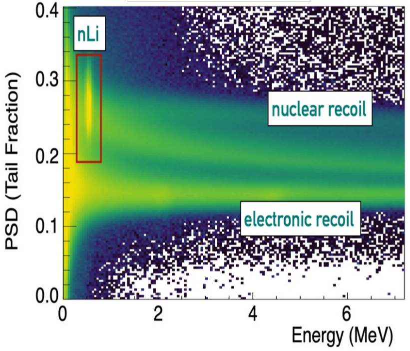
PROSPECT Detector



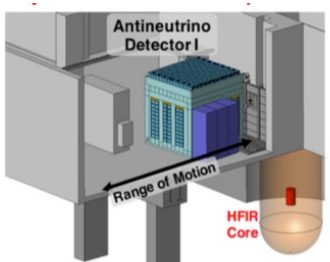
Antineutrino Detection:

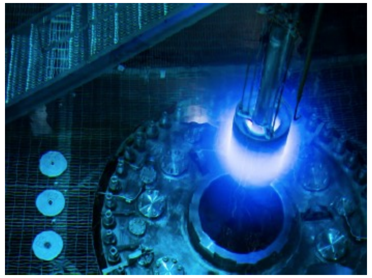
- PROSPECT detects antineutrinos via the Inverse Beta Decay (IBD) interaction
- Time-position correlation between prompt and delayed signal
- 14x11 array of 6LiLS (~4ton)
- Baseline: 6.7-9.2 m





Experiment Site:
High Flux Isotope Reactor (HFIR)

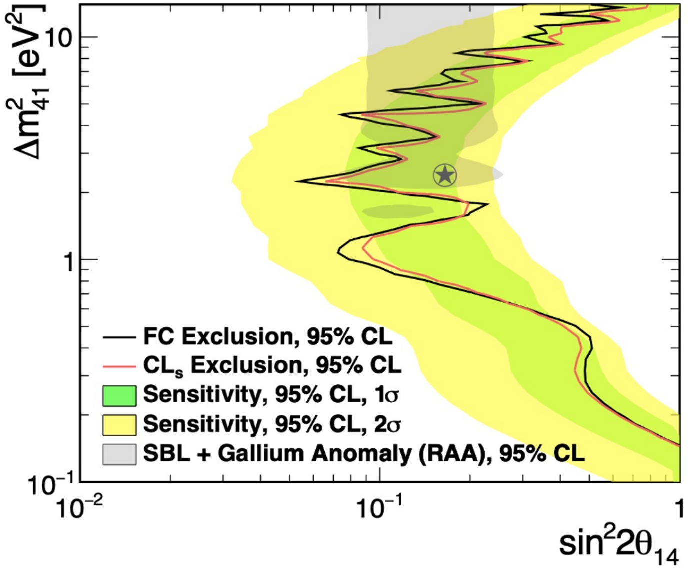


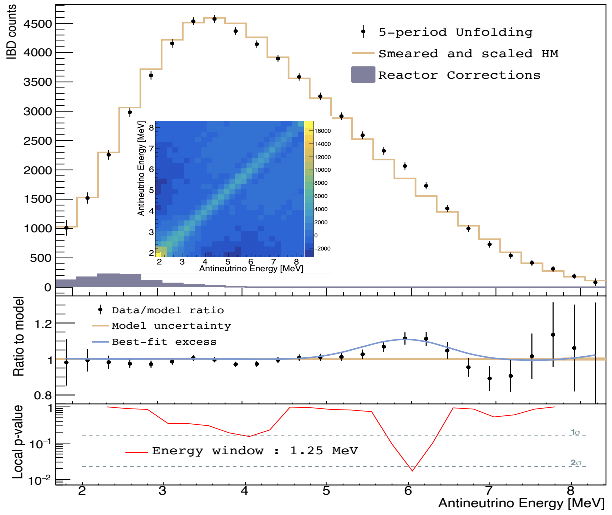


- 93% 235U Fuel
- 85 MW thermal power
- Compact core
- Huge flux in the few MeV range
- ~50% duty cycle for BG measurements

Results and plans from PROSPECT-I

2011 RAA paper & SNAC workshop,
2012 white paper motivated search for eV-scale sterile neutrinos,
2018 first physics limits from PROSPECT





- Performed direct test of the Reactor Antineutrino Anomaly,
  - RAA best-fit excluded: 98.5% CL
  - Data is compatible with null oscillation hypothesis (p=0.57)
- Helped establish new constraints on the origin of the data-model disagreement observed between 5-7 MeV
  - Likely due to an equal mismodeling of all fissile isotopes
- Led joint analyses with other experiments
  - STEREO and Daya Bay

- **PROSPECT has served as a fantastic professional development and training program for young scientists.**
  - **10 Ph.D. Theses**
  - **2 M.S. Theses**
  - **Multiple Postdocs and undergraduates as well**

First Oscillation Search
Phys. Rev. Lett. **121**, 251802 (2018)

First Spectrum Result
Phys. Rev. Lett. **122**, 251801 (2019)

Non-fuel reactor neutrinos
Phys. Rev. C **101**, 054605 (2021)

Improved Osc. + Spectrum
Phys. Rev. D **103**, 032001 (2021)

Boosted Dark Matter Search
Phys. Rev. D **104**, 012009 (2021)

Daya Bay/PROSPECT Joint Spectrum Analysis
Phys. Rev. Lett. **128**, 081801 (2022)

PROSPECT/STEREO Joint Spectrum Analysis
Phy. Rev. Lett **128**, 081802 (2022)

New Analysis Techniques

Final PROSPECT-I Spectrum
arxiv:2212.10669

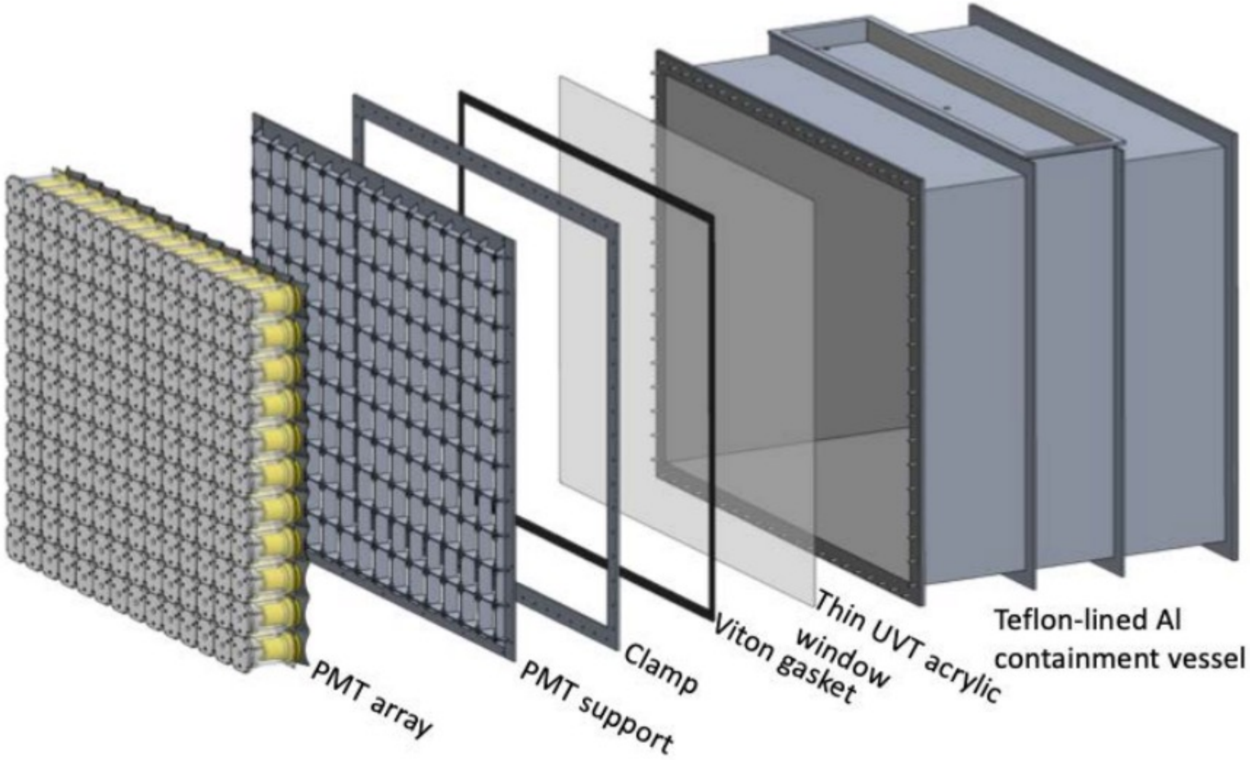
'Final' PROSPECT-I Oscillation

Absolute Flux Analysis

Correlated Background Study

Antineutrino Directionality

Next Phase of PROSPECT



High ~ 4:1 signal:background ratio

Planned ~2 year deployment at HFIR, ORNL

~50% reactor on-time

PROSPECT II

Retains successful elements of PROSPECT-I

- 14x11 optically segmented ^{6}Li-doped liquid scintillator with minimal shielding
- Located 7-9m from HEU core of HFIR (+ possible LEU site)

Moves PMTs out of liquid scintillator volume to avoid contact with other materials

Increases signal collection capacity with 20% longer segments, 20% increased ^{6}Li loading, longer data-taking period -> 10x effective statistics at HFIR

External calibration system instead of calibration tubes inside active volume, simplifies design

Designated to deploy at multiple sites

Physics opportunities:

- New HEU spectrum measurement with uncertainties at the level of model predictions
- Possible HEU/LEU measurement would mitigate the effect of systematic uncertainties
- Exclusion of the remaining Gallium Anomaly, RAA sterile neutrino oscillation phase space below ~10eV^2
- Test the claim made by Neutrino-4 at high Δm^2
- Address ambiguities in long-baseline physics

Neutrino Physics and R&D at ANNIE

The Accelerator Neutrino Neutron Interaction Experiment

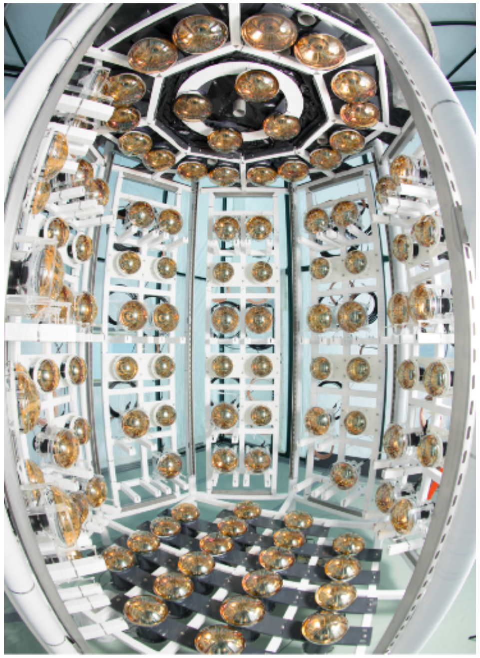
Andrew Mastbaum (Rutgers University), for ANNIE

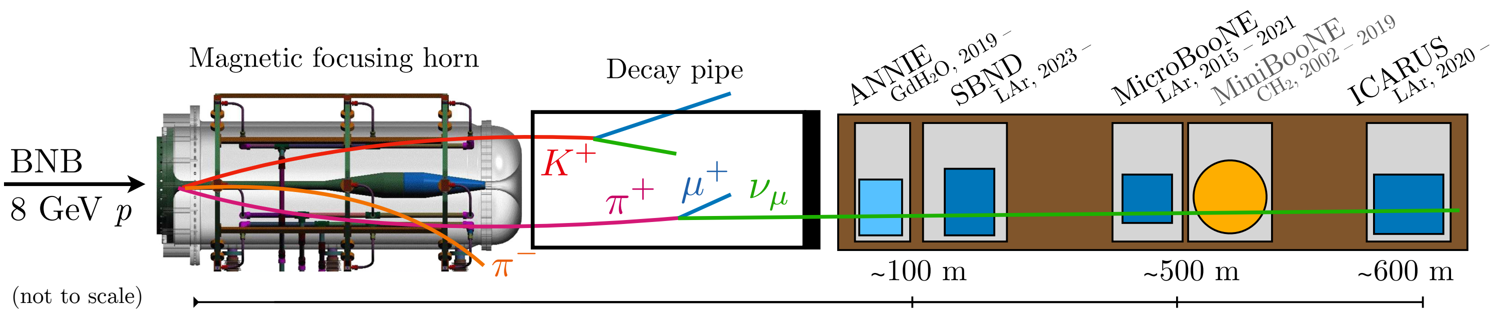
P5 Town Hall, Argonne Open Session

March 23, 2023

The ANNIE Detector

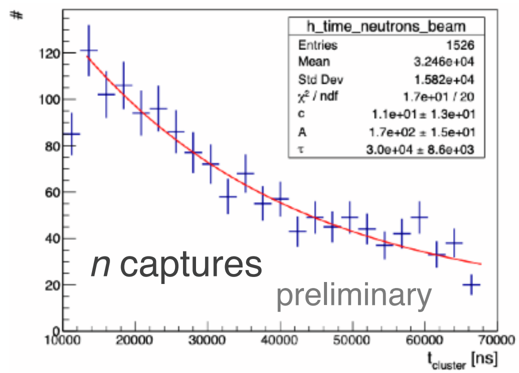
- **Located in a powerful GeV-scale accelerator neutrino beam**
  – Fermilab Booster Neutrino Beam (BNB): ~1 GeV ν_μ
  – Shared beamline with the Short-Baseline Neutrino (SBN) Program LArTPCs (SBND, MicroBooNE, ICARUS-T600)
- **A flexible, Gd-loaded water Cherenkov detector**
  – Water target loaded with Gadolinium
    - Excellent detection of neutrino-induced neutrons
    - Ability to deploy target sub-volumes (e.g. Water-based LS, GdWbLS) and various calibration sources
  – Light detection using PMTs and next-generation LAPPDs
  – Forward muon range detector for reconstructing high-momentum tracks, front veto to reject upstream activity

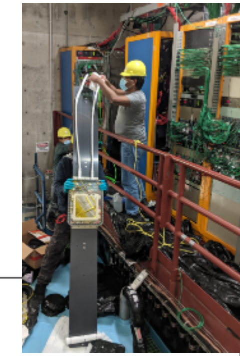


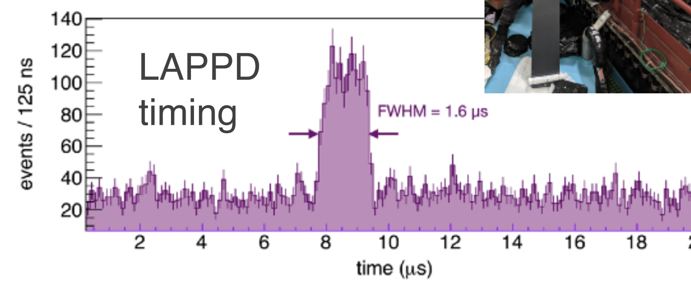


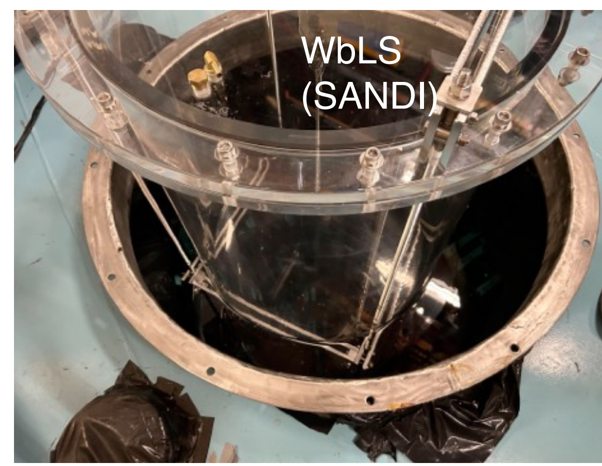
ANNIE in the broader program

- **A suite of targeted neutrino-nucleus interaction measurements**
  - Neutrino-induced neutron production
  - Characterizing backgrounds for future DSNB and proton decay searches
  - Leveraging BNB experiments for precision multi-target cross section measurements (argon/water)
    - Key cross section ratios and correlated hadron production constraints
  - Snowmass LoI: [Physics Opportunities at ANNIE]
- **A flexible R&D testbed for future large detectors**
  - Gd loading: 1st Gd-H_2O target in a neutrino beam
  - LAPPDs: First neutrinos on LAPPDs (2022)
    - Multiple LAPPDs deployed now, more coming
  - WbLS: Water-based LS sub-volume deployed now
    - Future plans for a full WbLS fill, opportunity to prototype e.g. Theia beam (LBL) physics
  - Snowmass LoI: [ANNIE Detector R&D]





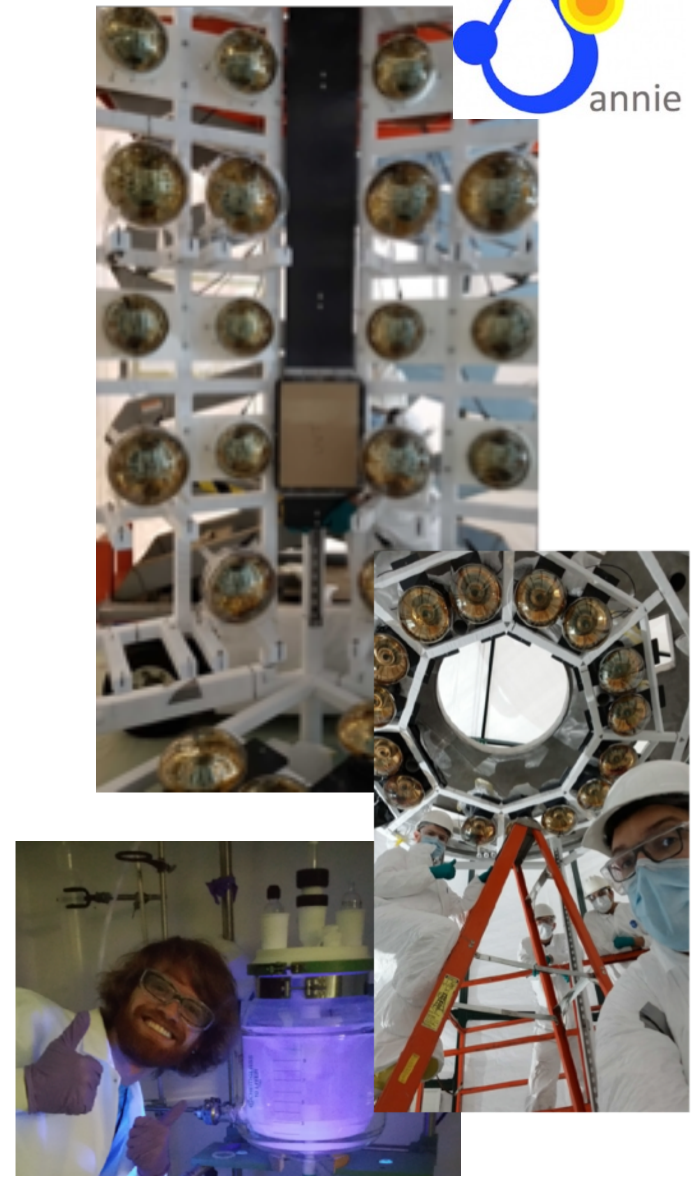




Role of small-scale experiments

annie

- Small-scale experiments offer clear benefits to the particle physics community
  - Targeted measurements (physics and R&D) inform the larger programs
  - Flexibility to address evolving needs
- Projects provide an ideal training ground for early career scientists
  - Experience all facets of experimental physics
  - Broad expertise for executing physics projects, skills the technical workforce
- **Realizing these benefits requires robust and predictable funding in the coming years**
  - Such projects have a high impact-to-cost ratio
  - Strong support enables creative, high-impact science and excellent training opportunities



Trinity: UHE Earth-skimming Neutrino Detector

Date: 2023/03/23

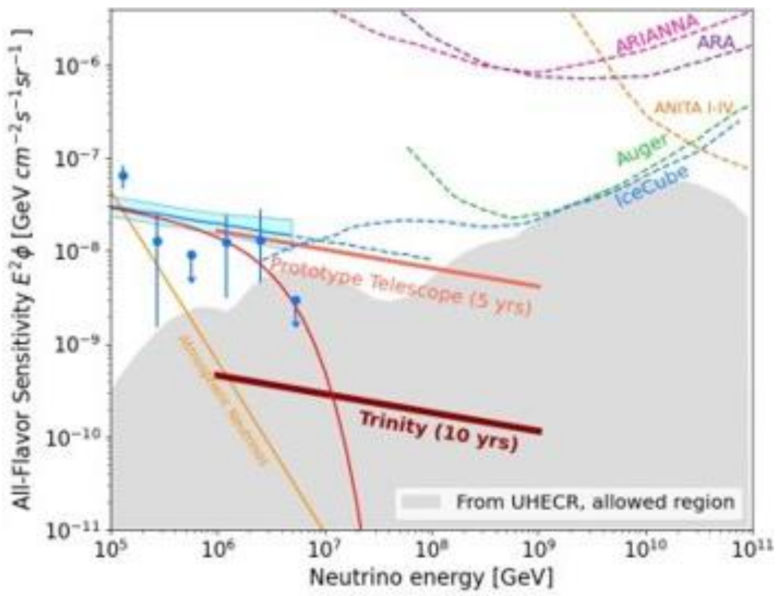
Auther: Mathew Potts

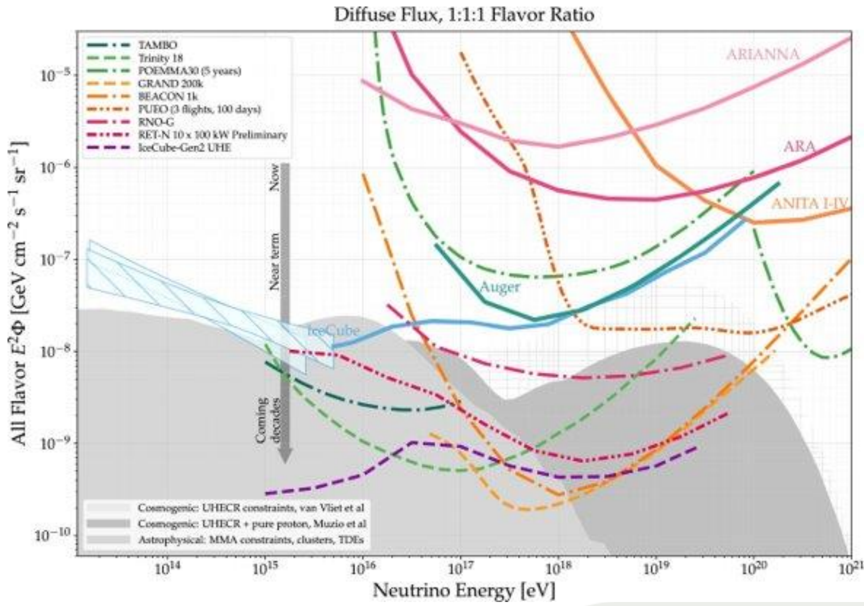
Abstract: Trinity is a next-generation imaging air Cherenkov telescope array that utilizes an earth-skimming technique to detect ultra-high-energy neutrinos. Its sensitivity will play a crucial role in filling the gap between the observed astrophysical neutrinos observed by IceCube and the predicted sensitivity of radio UHE neutrinos detectors. As proof of the concept, we are building a smaller demonstrator telescope in Milford, Utah. I will show the progress on bringing the Trinity demonstrator online and talk about how it fits into our plans for the full Trinity array.

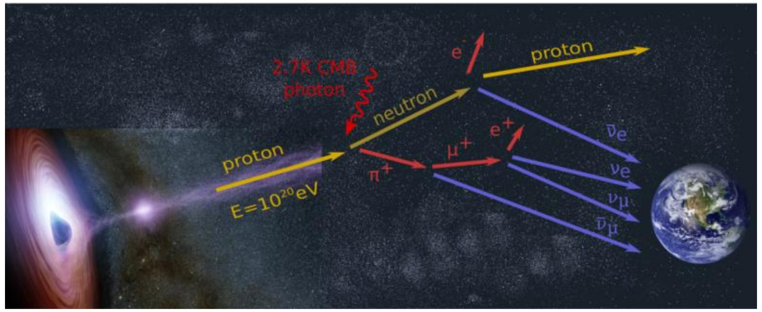
Georgia Tech

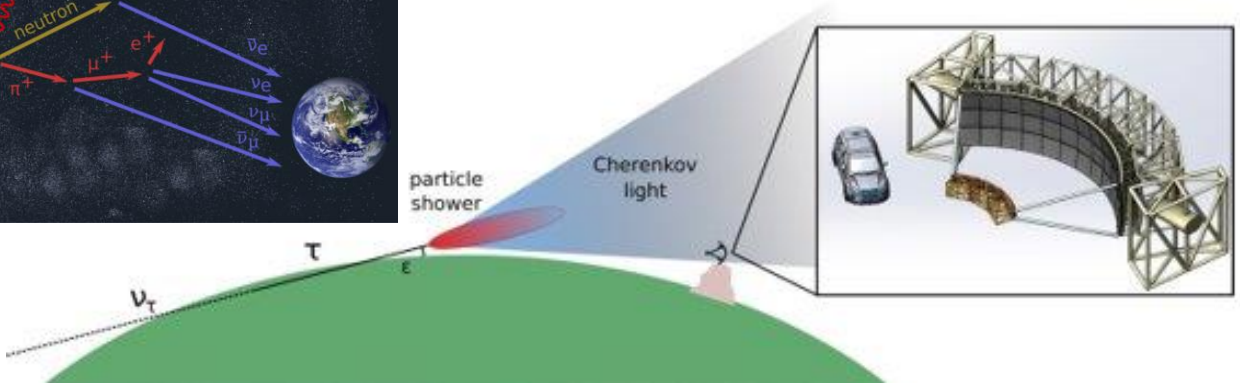
Science of the Trinity Observatory

- 3 sites composed of 6 Imageing Air Cherenkov Telescopes (IACTs)
  - Telescopes 5° × 60° FoV
- Observes the horizon to view upward going Extensive Air Showers (EAS) caused by Tau neutrinos interacting in the Earth's crust
- Trinity is expected to be sensitive to neutrinos with energies between 1-10,000 PeV



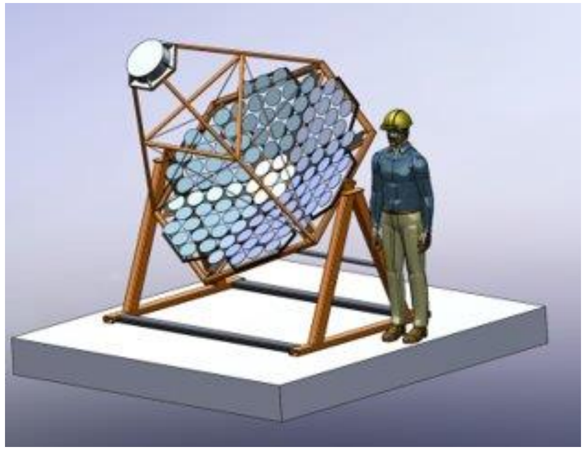






Trinity Demonstrator

- Located near Milford, Utah on Frisco Peak
- The objectives of the Demonstrator are to study potential sources of background, to prove remote operation, and to demonstrate the technological
- Last September 2022 the telescope building got installed, weather system, cameras, remote door control, and control PC
- Planned deployment of Demonstrator telescope in May 2023



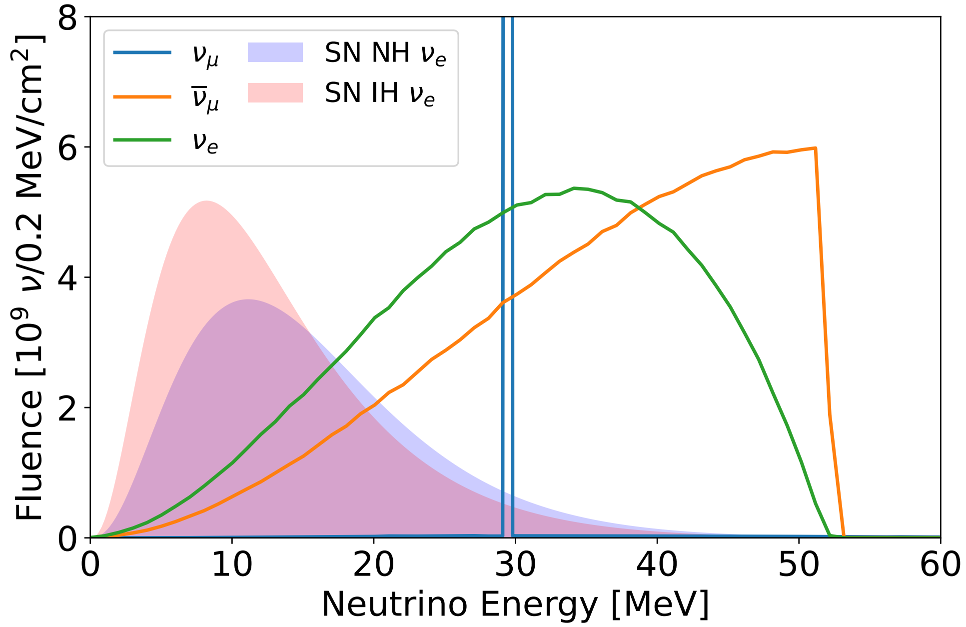
Georgia Tech

Future Physics Opportunities at the Oak Ridge National Laboratory Spallation Neutron Source

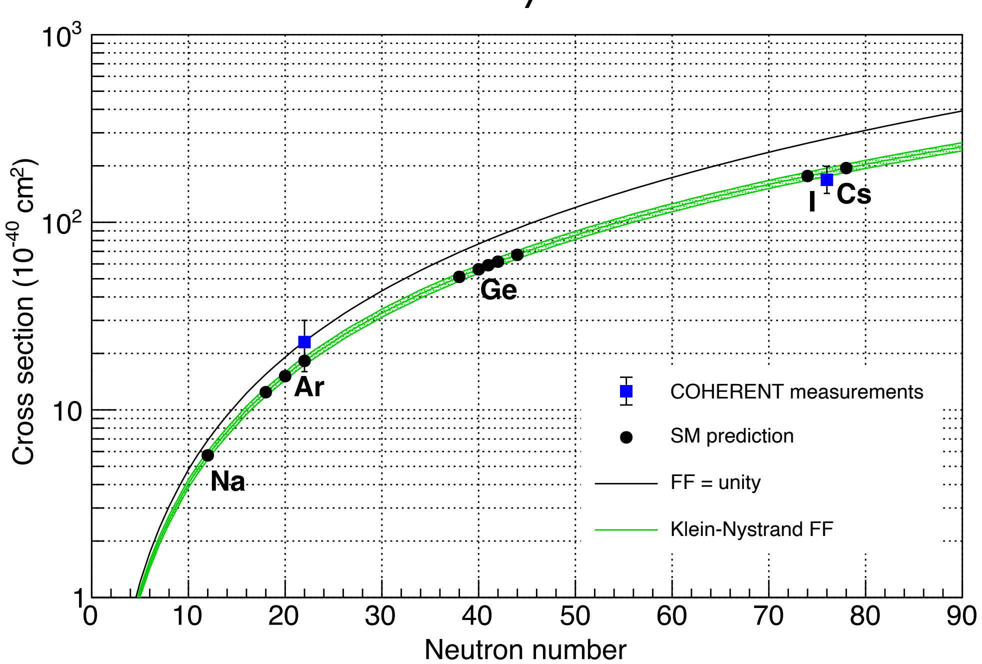
Jason Newby (ORNL), Dan Pershey (Duke),
Rebecca Rapp (W&J College), Yun-Tse Tsai (SLAC)
P5 Town Hall Open Session
March 24th, 2023

Physics with SNS Neutrinos

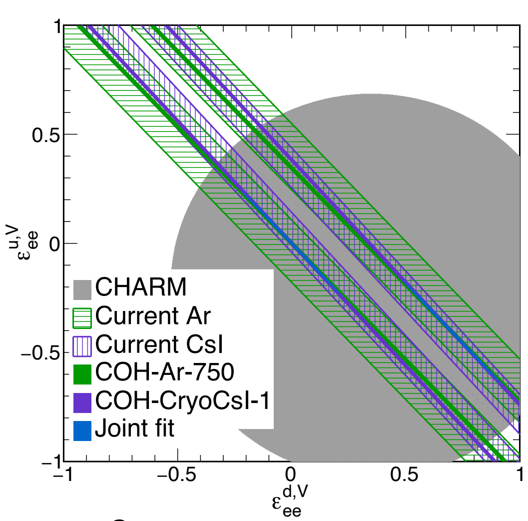
SNS ν: π^+ decay-at-rest



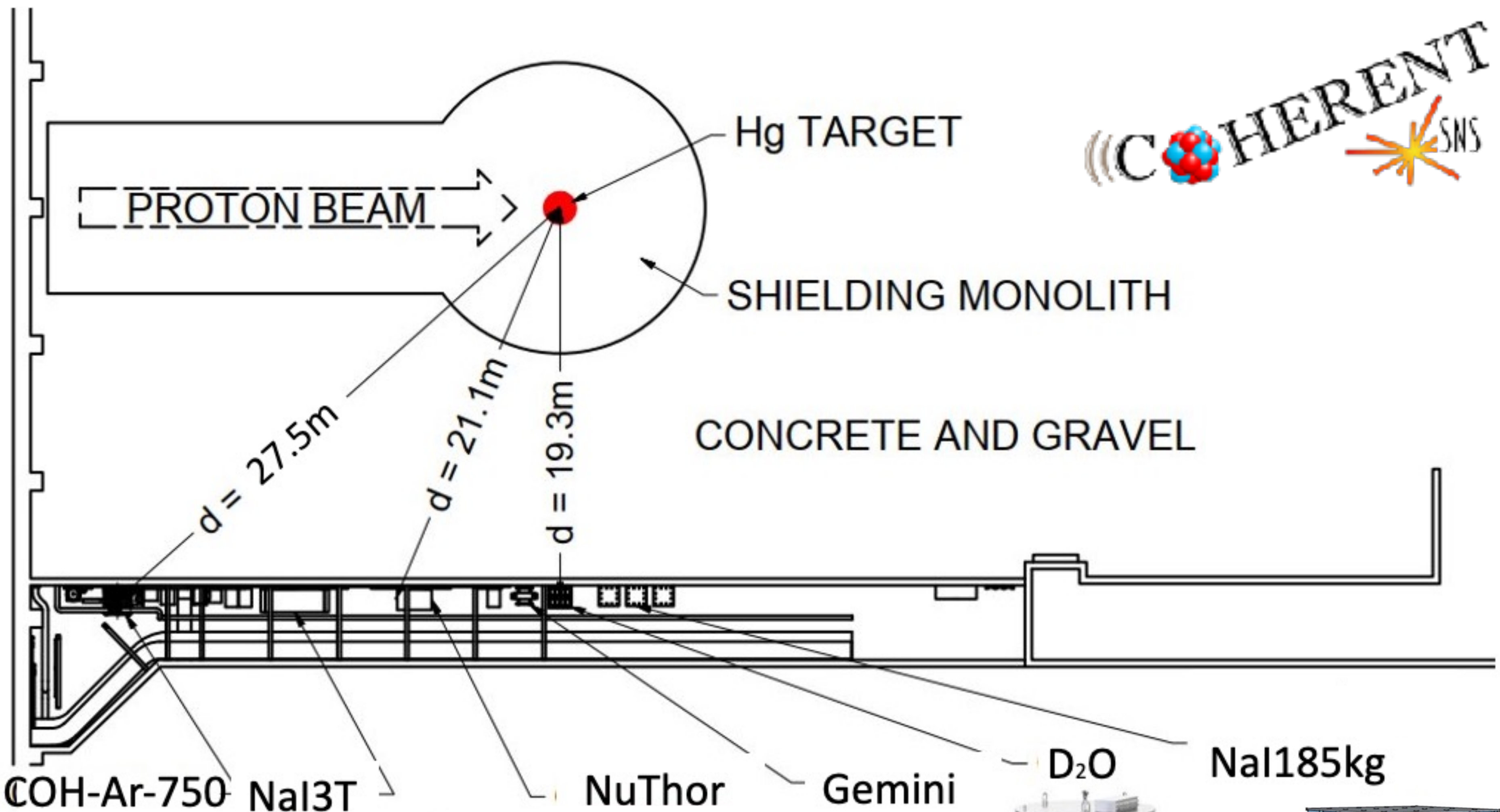
CEvNS Results by COHERENT



- Coherent Elastic ν-Nucleus Scattering (CEvNS), discovered in 2017 by COHERENT here
- Test SM and probe BSM by precisely measuring CEvNS
- Inelastic ν interactions: relevant to supernova neutrino measurements in DUNE



Current & Potential Detectors



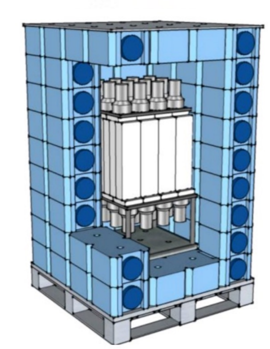
750-kg LAr scintillation detector Under construction

2425-kg NaI Being deployed

52-kg ^{232}Th ν_e-Th CC Since 2022

18-kg Ge Since 2022

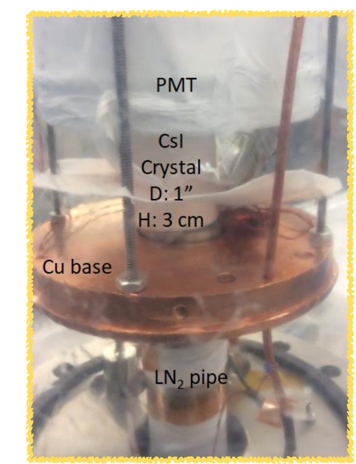
2x592-kg D_2O Module 1 in commissioning



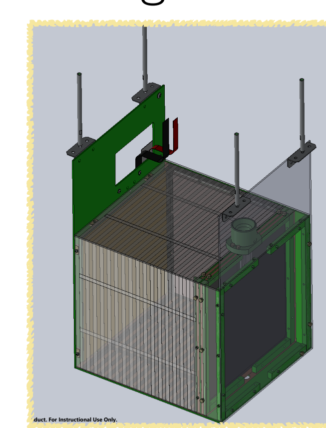
185-kg NaI ν_e-I CC Since 2016

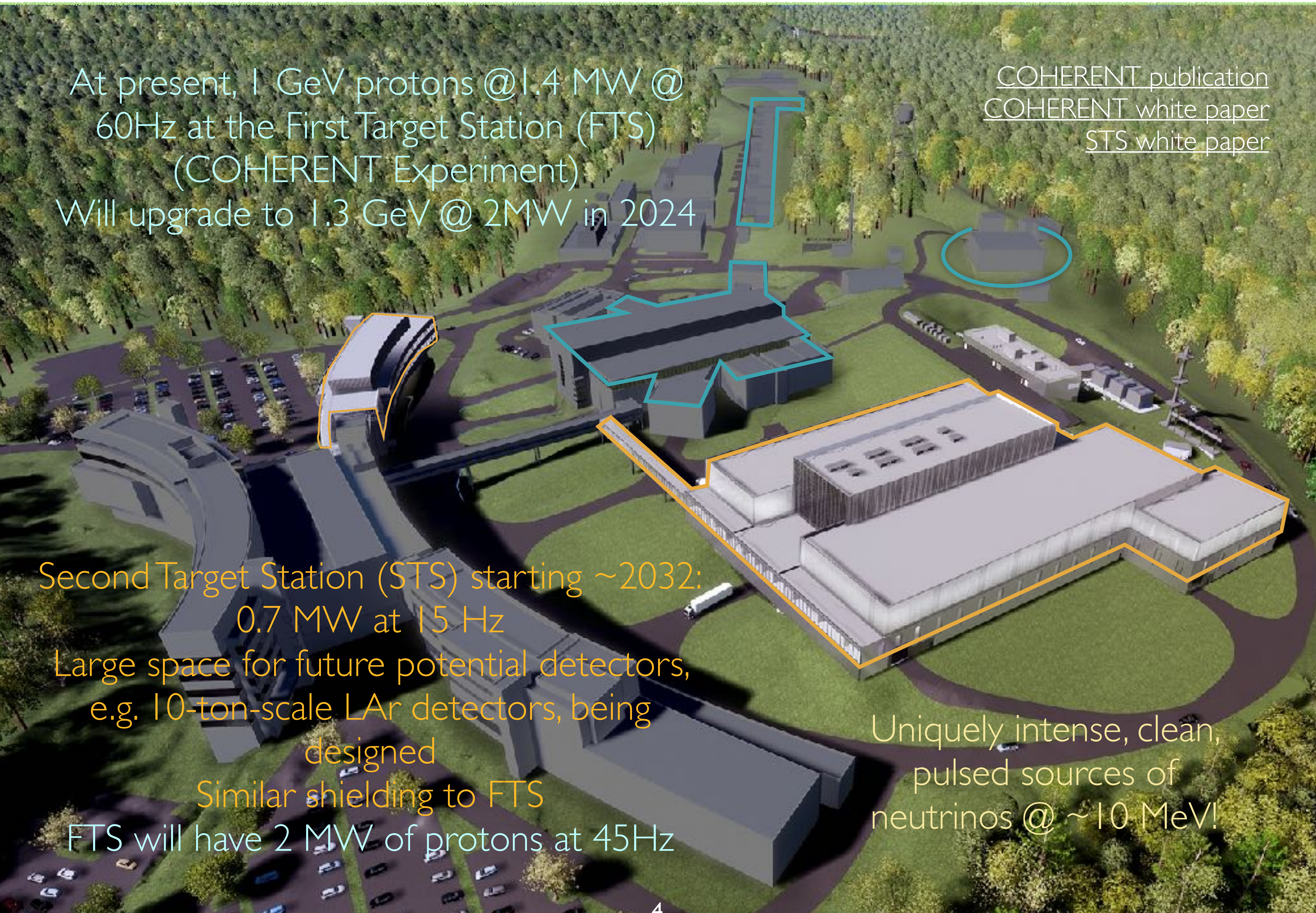
Potential future additions

10-kg Cryo-CsI



250-kg LArTPC





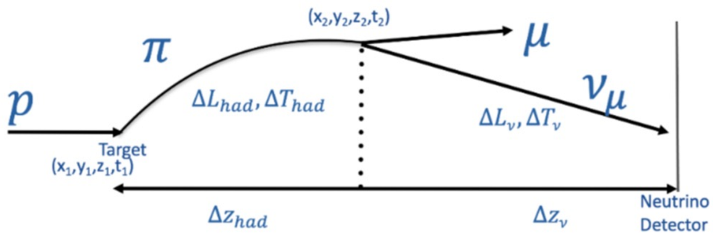
At present, 1 GeV protons @1.4 MW @ 60Hz at the First Target Station (FTS) (COHERENT Experiment)
Will upgrade to 1.3 GeV @ 2MW in 2024

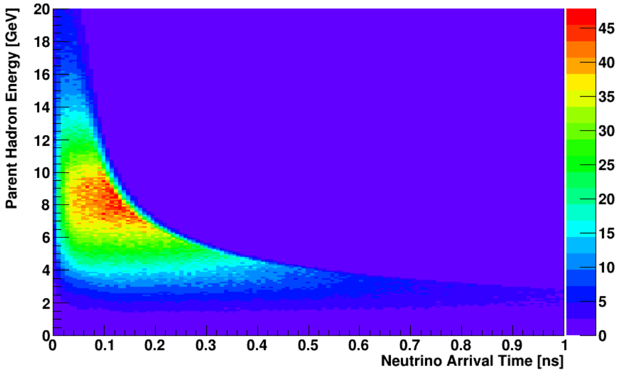
COHERENT publication
COHERENT white paper
STS white paper

Second Target Station (STS) starting ~2032:
0.7 MW at 15 Hz
Large space for future potential detectors, e.g. 10-ton-scale LAr detectors, being designed
Similar shielding to FTS
FTS will have 2 MW of protons at 45Hz

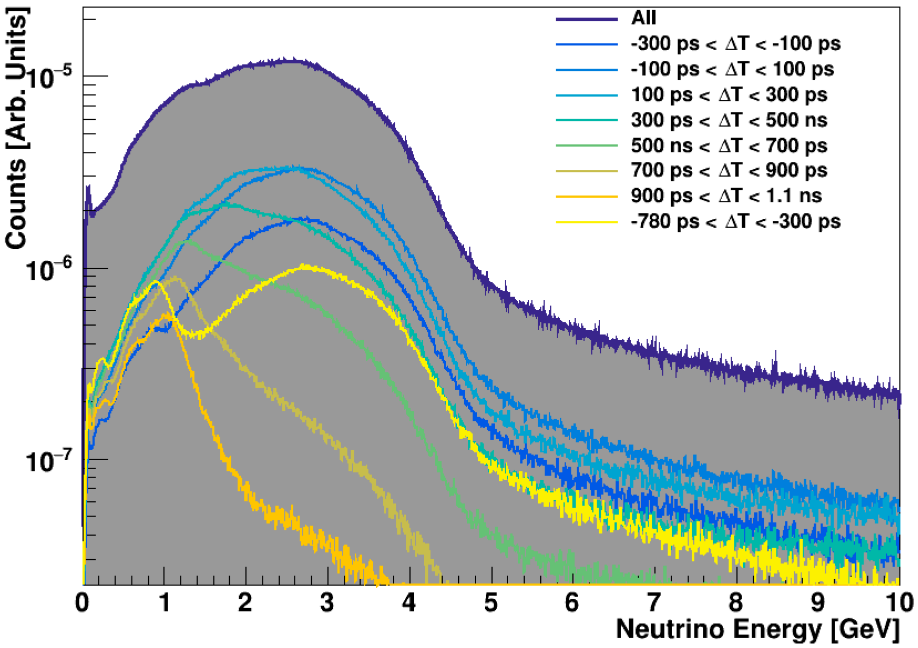
Uniquely intense, clean, pulsed sources of neutrinos @ ~10 MeV!

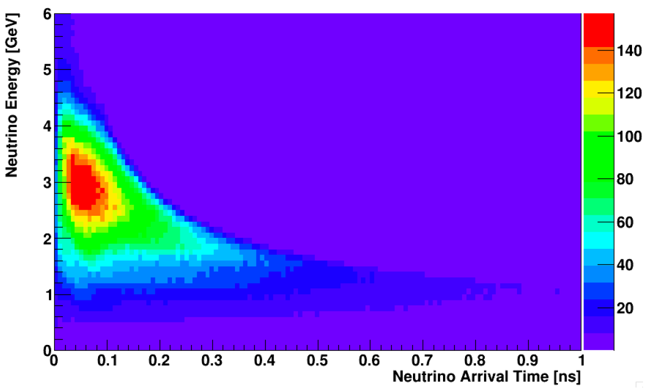
Neutrino Beam Timing – Stroboscopic Approach





Arrival time difference between neutrinos from relativistic hadrons and neutrino from hadron of energy E





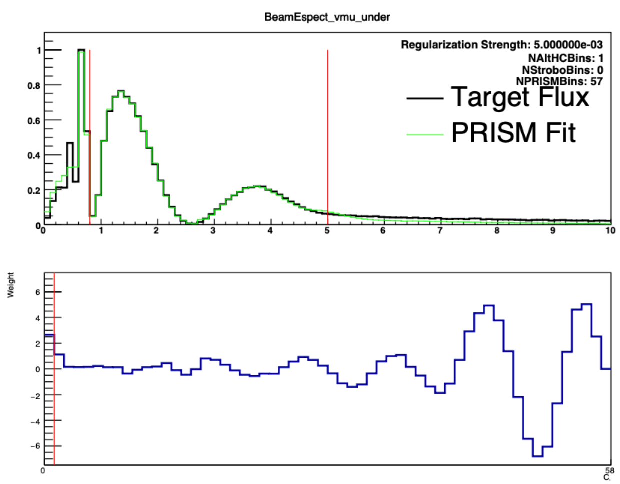
Relative neutrino arrival times versus neutrino energies for all neutrinos with simulated data of the LBNF beam

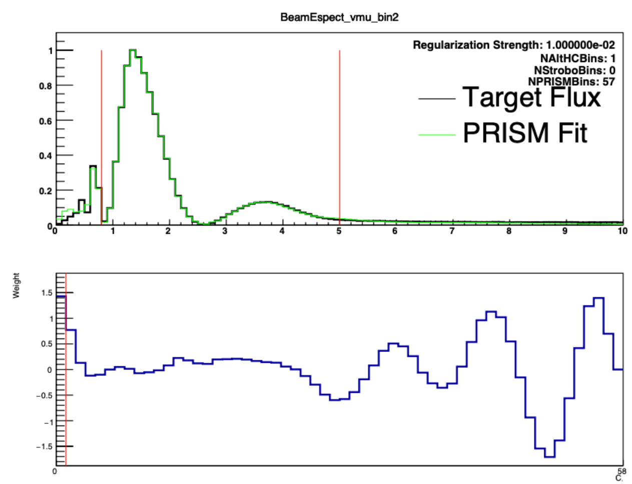
Motivation

Number of Near Detector events = Flux · Cross section · Detector effects

Number of Far Detector events = Flux · Oscillation probability · Cross section · Detector effects

- If both flux and cross section have uncertainties, cannot unambiguously tell if we have both correct in models or both wrong in ways that result in approximately correct event rate prediction
- **Stroboscopic approach – can be applied to both Near & Far detectors**
  - Oscillated time integrated spectrum of Far Detector can be fitted to PRISM and Stroboscopic approaches in Near Detector
  - Can provide Far Detector oscillated time slices





PRISM fits to oscillated Far Detector time bins

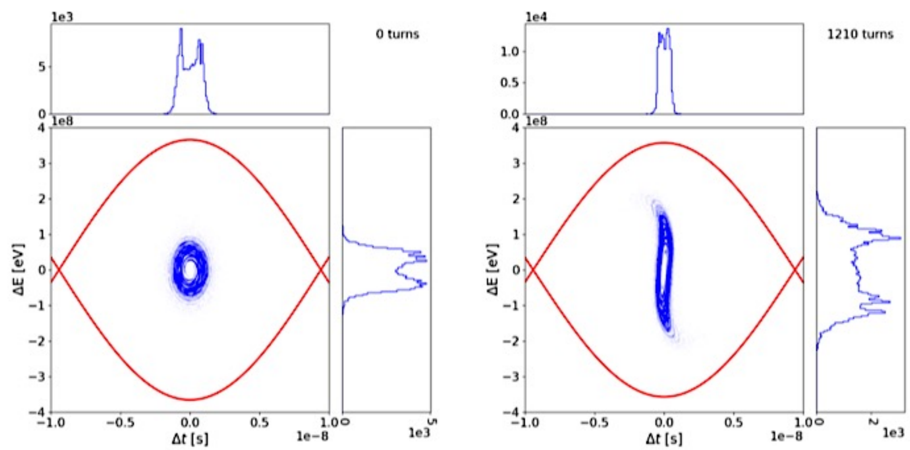
Application of Stroboscopic Approach

Application requires efforts in:

- Creation of short (O(100 ps)) proton bunch length
- Detectors with fast timing to get equivalent time resolution
- Synchronization b/w time at detector & time of bunch-by-bunch proton

Precision timing in DUNE ND – possible with minor upgrades, in FD later design modification possible

Use bunch rotation at MI to create Narrow Bunches:



Minimal bunch length of 330 ps occurs ~ 1210 revolution

- ANNIE equipped with Large Area Picosecond Photodetectors (LAPPDs) → better vertex reconstruction, improved background rejection → together with precision timing in beam delivery and time synchronization tools developed, first proof of principle possible with ANNIE
- With tools developed for time synchronization, precision timing can be applied to future oscillation experiments with fast detectors - there is an excellent opportunity here to think about fast timing for LAr-TPCs

Next Generation Instrumentation for Ultra-High-Energy Cosmic Rays (UHECR)

based on the Snowmass CF7 Whitepaper on UHECR with about 100 authors and 200+ endorsers → arxiv: 2205.05845

UNIVERSITY OF DELAWARE
BARTOL RESEARCH INSTITUTE

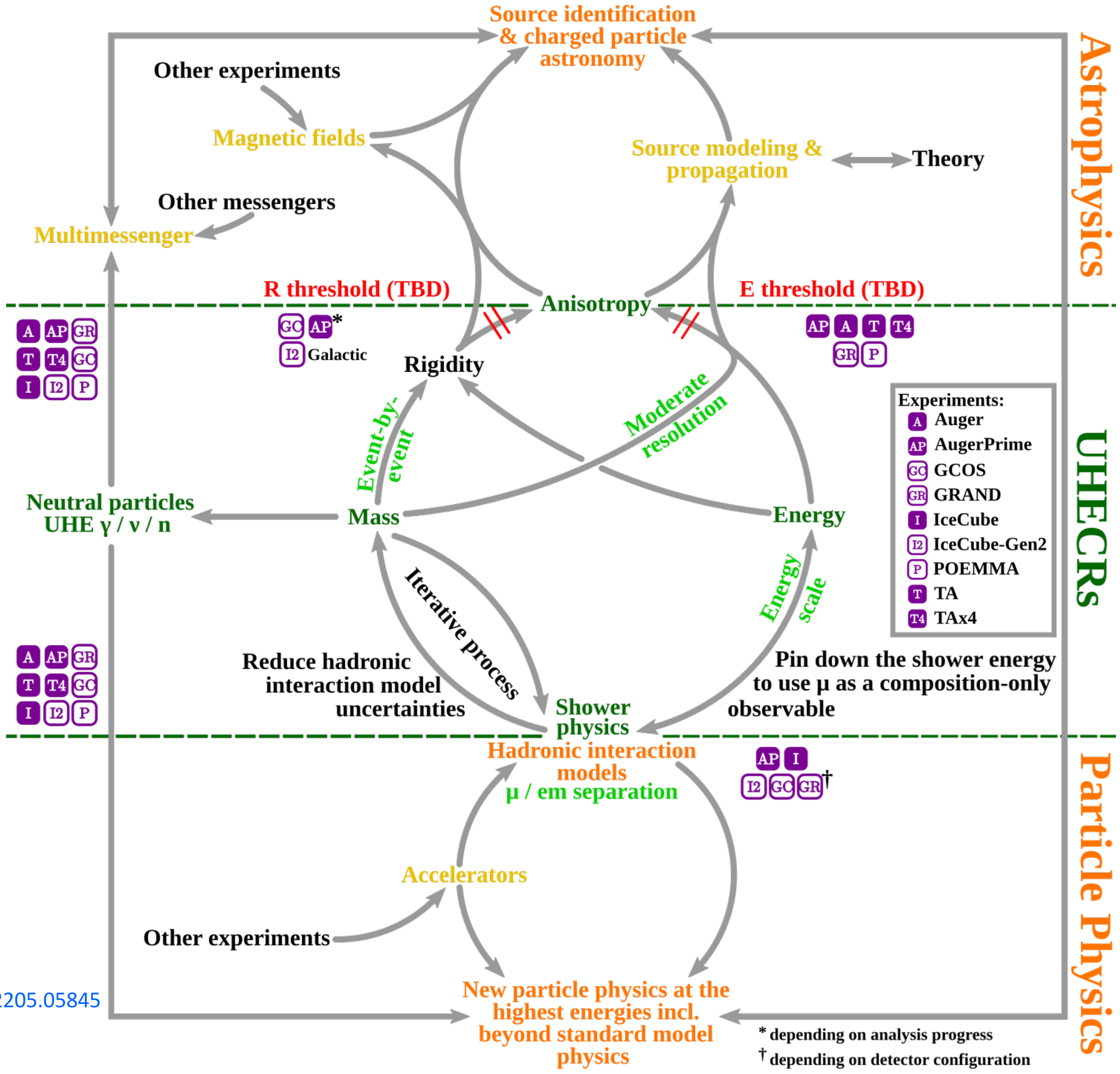
Presenter:
Frank G. Schroeder

Summary Table: Major experiments for UHECR astrophysics *and* particle physics at $10^{17} - 10^{21}$ eV.

	Experiment	Feature	Cosmic Ray Science*	Timeline
current	Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
current	Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
≤ EeV	IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement → IceCube-Gen2 deployment → IceCube-Gen2 operation
> EeV	GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300 → GRAND 10k → GRAND 200k multiple sites, step by step
> EeV	POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	JEM-EUSO program → POEMMA
> EeV	GCOS	Hybrid array with $X_{\max}$ + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site → GCOS further sites

Timeline axis: 2025, 2030, 2035, 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.



2205.05845

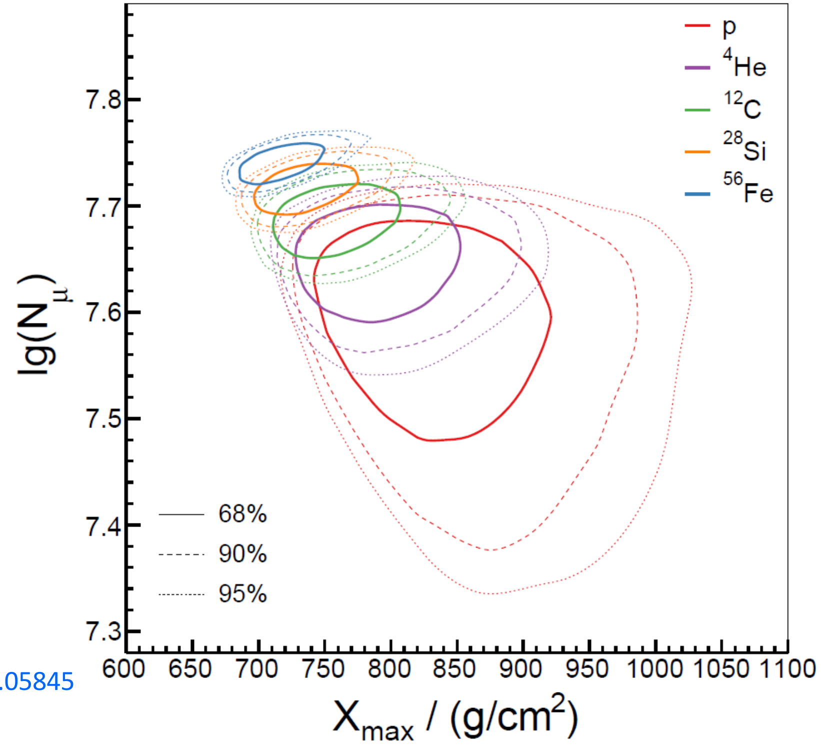
Complementary Approaches

Two types of next-generation instruments needed to for future UHECR science

1. huge exposure combined with accurate knowledge of average mass composition
   - space-based stereo observation P **POEMMA** → see remarks by Tonia Venters
   - ground-based multi-site international radio array for neutrinos and UHECR GR **GRAND**
2. event-by-event rigidity through high accuracy air-shower detection GC **GCOS**
   - particle astrophysics by back-tracing through magnetic fields when rigidity is known
   - more stringent tests of hadronic interaction model to investigate, e.g., muon puzzle
   - better identification of primary particle type also helps BSM searches, such as SHDM

Global Cosmic-Ray Observatory (GCOS)

- GCOS will be a 40,000 km² ground array of hybrid detectors distributed among several sites
  - joint sites with GRAND radio arrays possible: huge statistics, but no event-by-event mass separation
- Event-by-event mass separation requires simultaneous detection of muons + em. shower maximum (X_{max})
- U.S. participation requires **R&D during this decade**, preparing for a **possible U.S. site in the next decade**



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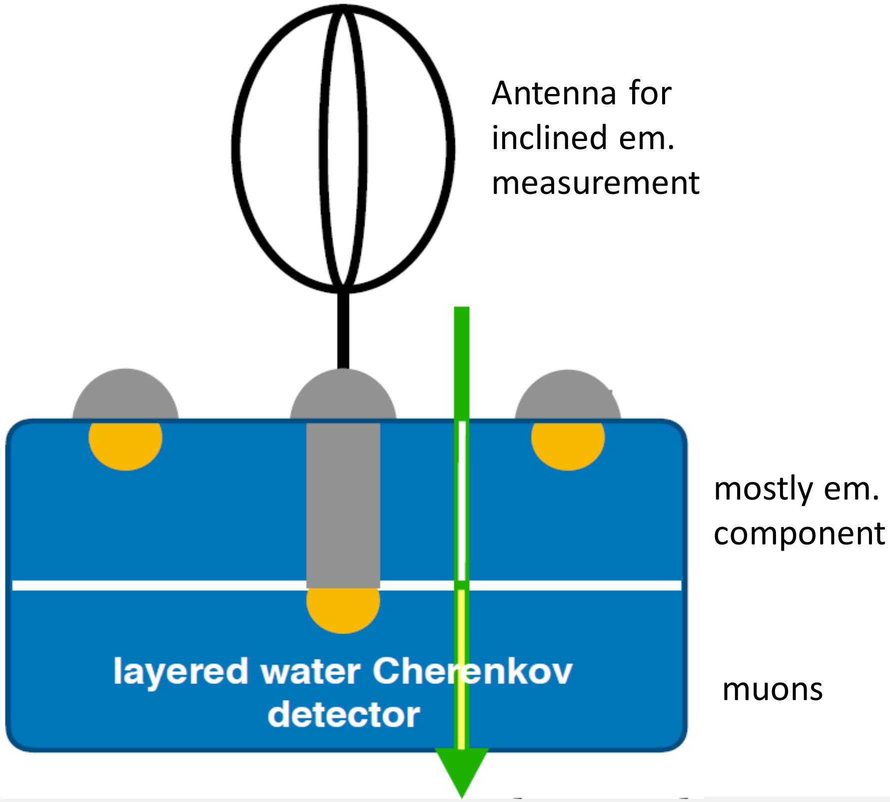
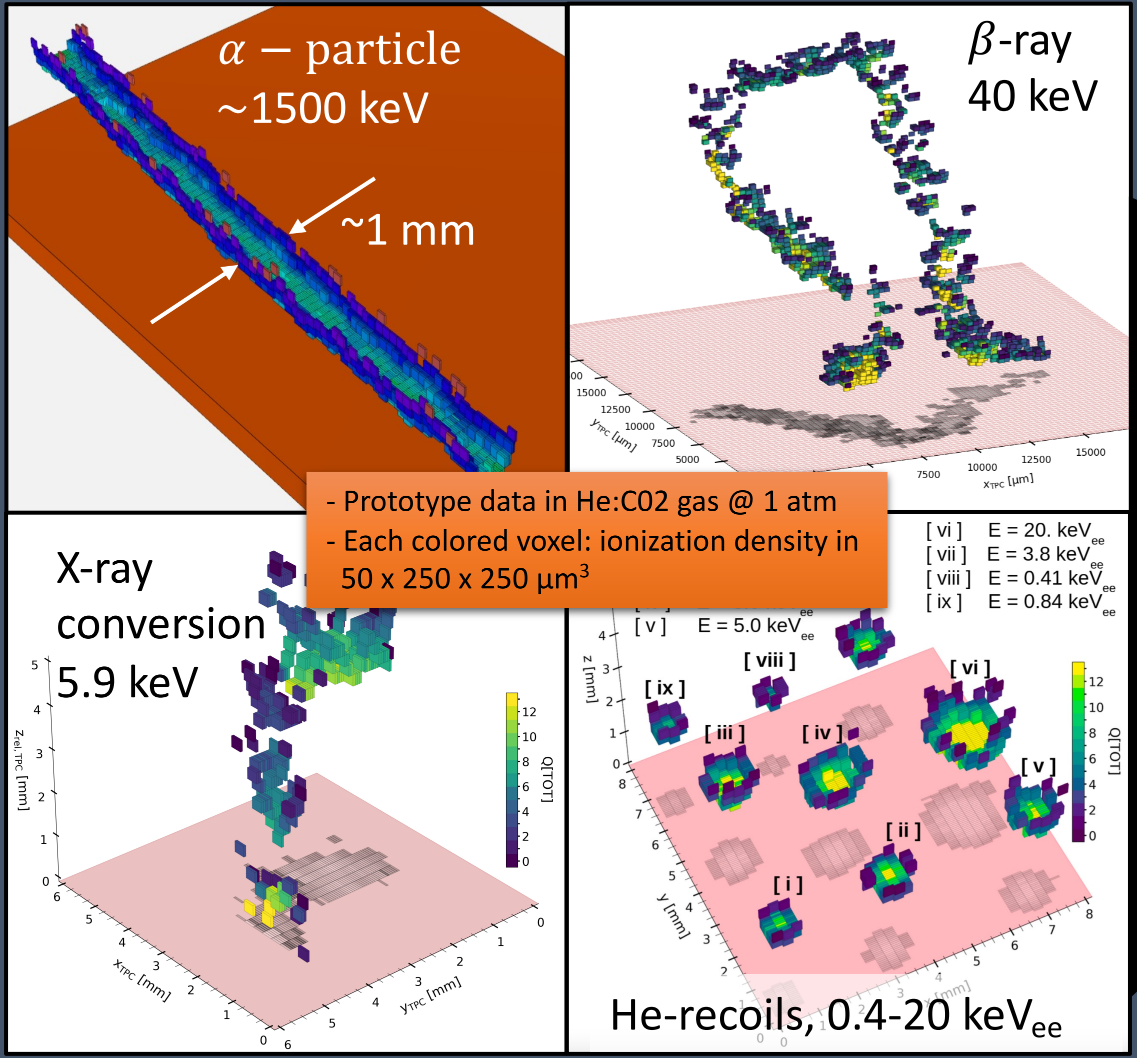
Left:
Complementary mass sensitivity of muons and X_{max} is needed for event-by-event rigidity estimate

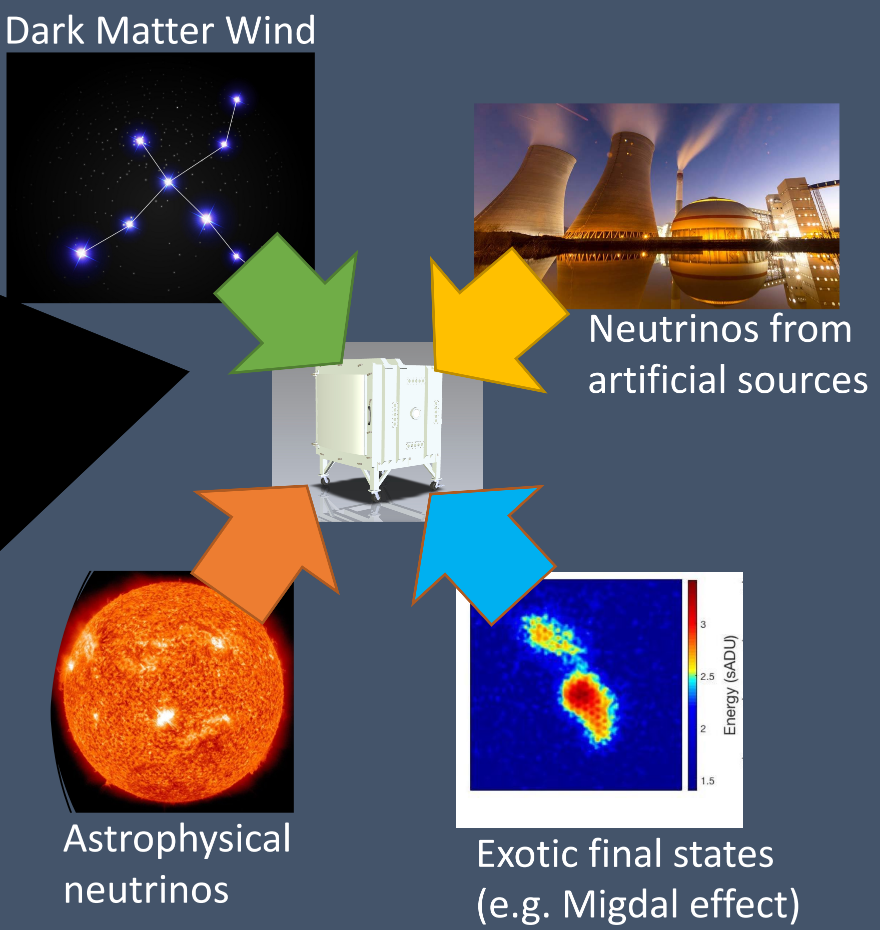
Right:
Possible particle detector of the GCOS array. Next steps: prototypes, optimizations and cross-calibration



CYGNUS: New Physics Capabilities from Recoil Imaging



"recoil imaging": detection of detailed ionization topology in gas TPCs



- A Snowmass working group of 167 physicists considered the case for "recoil imaging" (arXiv:2203.05914)
- Topological and directional reconstruction of low-energy nuclear and electronic recoils enables new experiments

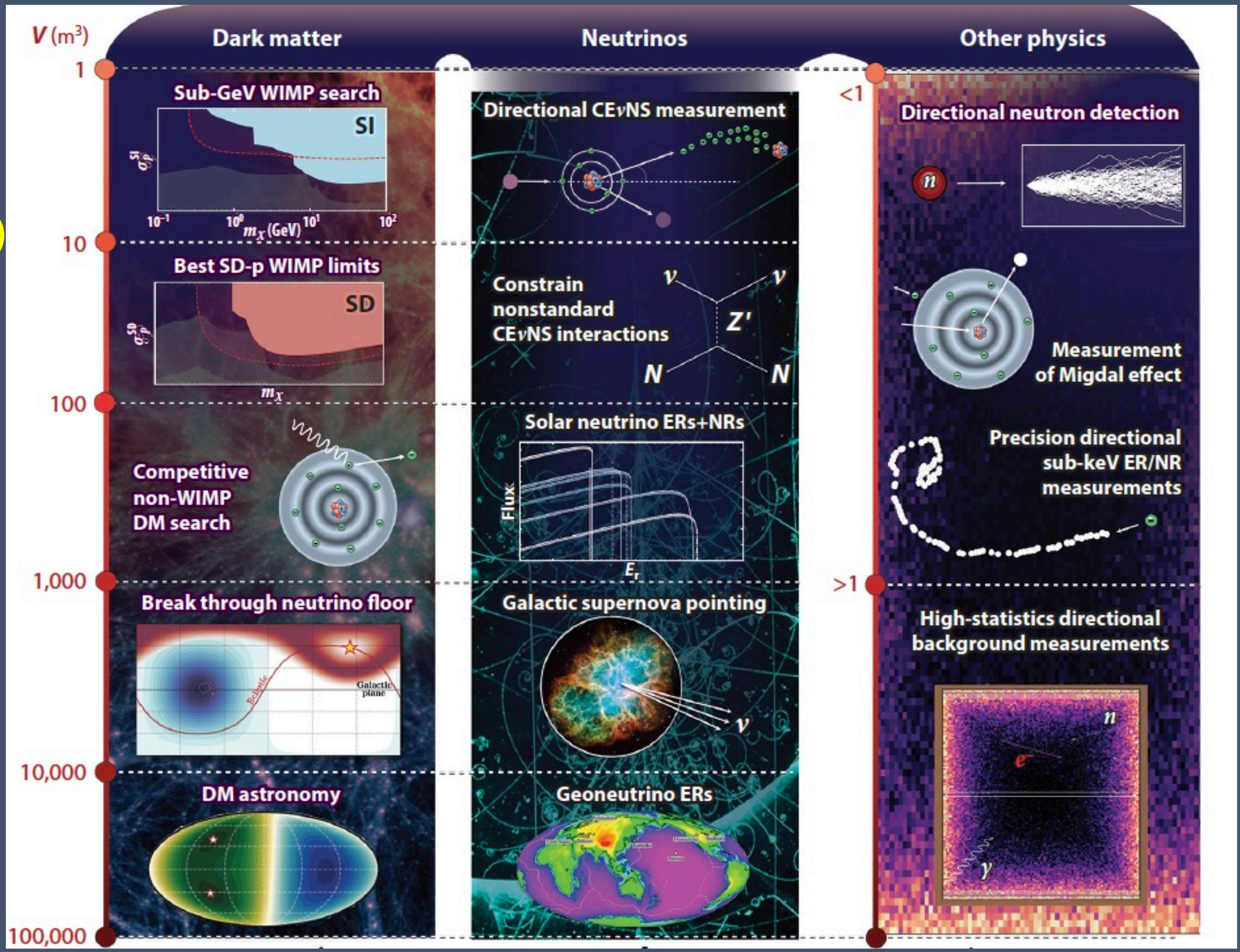
Opportunities for a 30+ year physics program

arxiv:2102.04596

Approx. volume of gas TPC required.
Expect 10 m^3 modules eventually

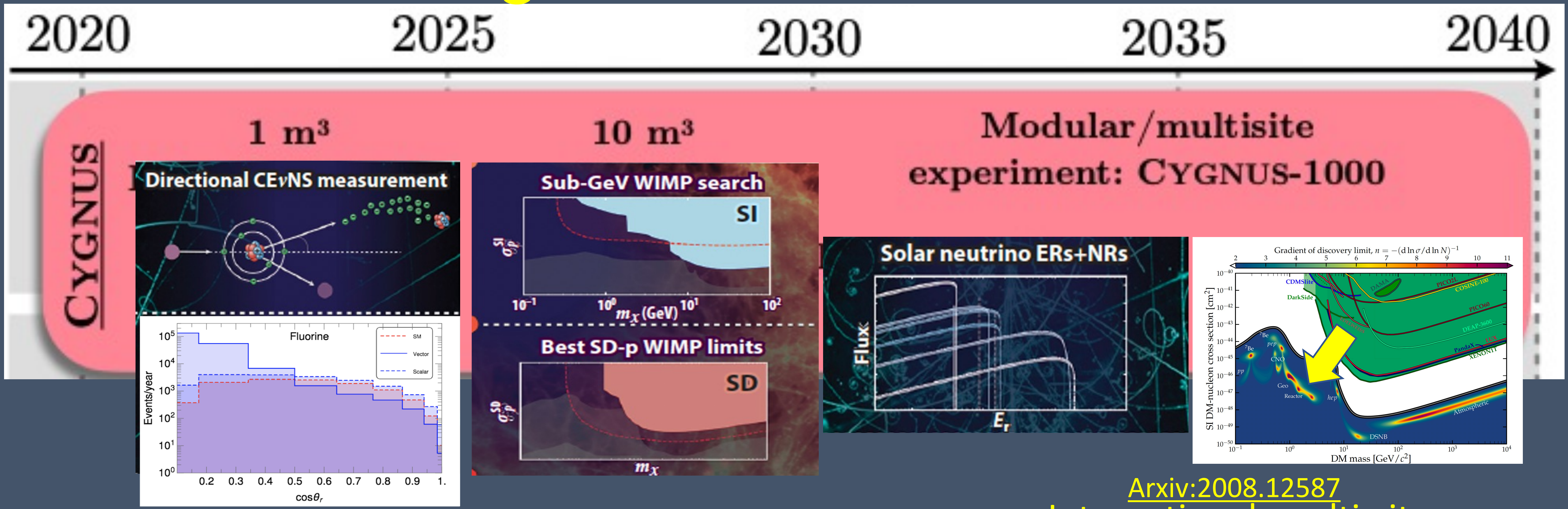
Exposure, size

- Quenching factor and recoil physics (TUNL)
- Migdal Effect measurement
- Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) at ORNL (SNS) or Fermilab (NuMI and later LBNF)
- Competitive DM limits in SI and SD
- CEνNS and e-recoils from solar neutrinos
- Efficiently penetrating the LDM ν floor
- Observing galactic DM dipole
- Measuring DM particle properties and physics
- Geoneutrinos
- WIMP astronomy



- New physics opportunities for each factor of 10 increase in exposure
- Both guaranteed measurements (yellow text) and novel, exciting searches --- across frontiers!

CYGNUS: US Program Vision & P5 Ask



Arxiv:2008.12587

SNS, Oak Ridge, TN	SURF, Lead, SD	International, multi-site
$1M	$5M	$50M, for 1000m^3 in the U.S.
Directional BSM-search in CEvNS	World-leading DM limits	DM search in the neutrino fog!

- 3 years of R&D (5 universities, three national labs). Establish electron counting & 1-keV recoil directionality: $2M / year
- Directional BSM search in 1 m^3 ν-scattering experiment, aboveground — $1M (hardware only)
- Radio-pure 10 m^3 experiment, underground (DM) — $5M (hardware only)
- MIE for large-scale, underground observatory (solar neutrinos + DM below neutrino floor) — $50M (hardware only)

Cosmic Rays and Neutrinos with POEMMA and EUSO-SPB2

Clinching Space to Open a New Gateway into Fundamental Physics

Tonia Venters

Astrophysics Science Division

NASA Goddard Space Flight Center

Earth Image Credit: Google Earth

Probe of Extreme Multi-Messenger Astrophysics

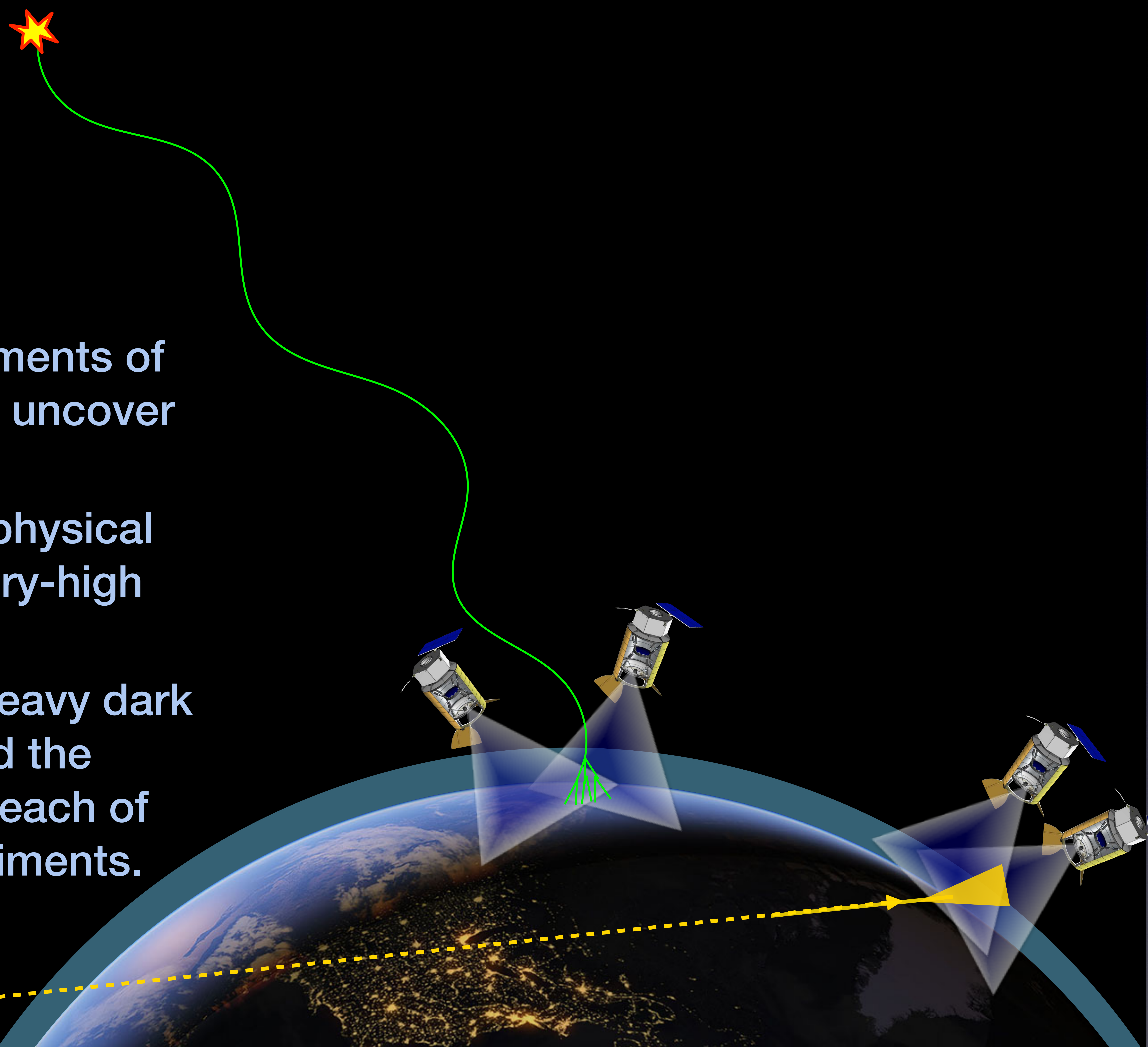
A multi-messenger probe to perform transformational measurements of UHECRs and cosmic neutrinos.

Collaboration: 70+ scientists from 21+ institutions and > 10 countries and leveraging experience from OWL, JEM-EUSO, Auger, TA, VERITAS, CTA, Fermi, and Theory

Earth Image Credit: Google Earth

Science Goals:

- Perform high statistics measurements of ultra-high energy cosmic rays to uncover their sources.
- Pioneer rapid follow-up of astrophysical transients via observations of very-high energy neutrinos from space.
- Search for signatures of super-heavy dark matter and other physics beyond the Standard Model, extending the reach of terrestrial particle physics experiments.

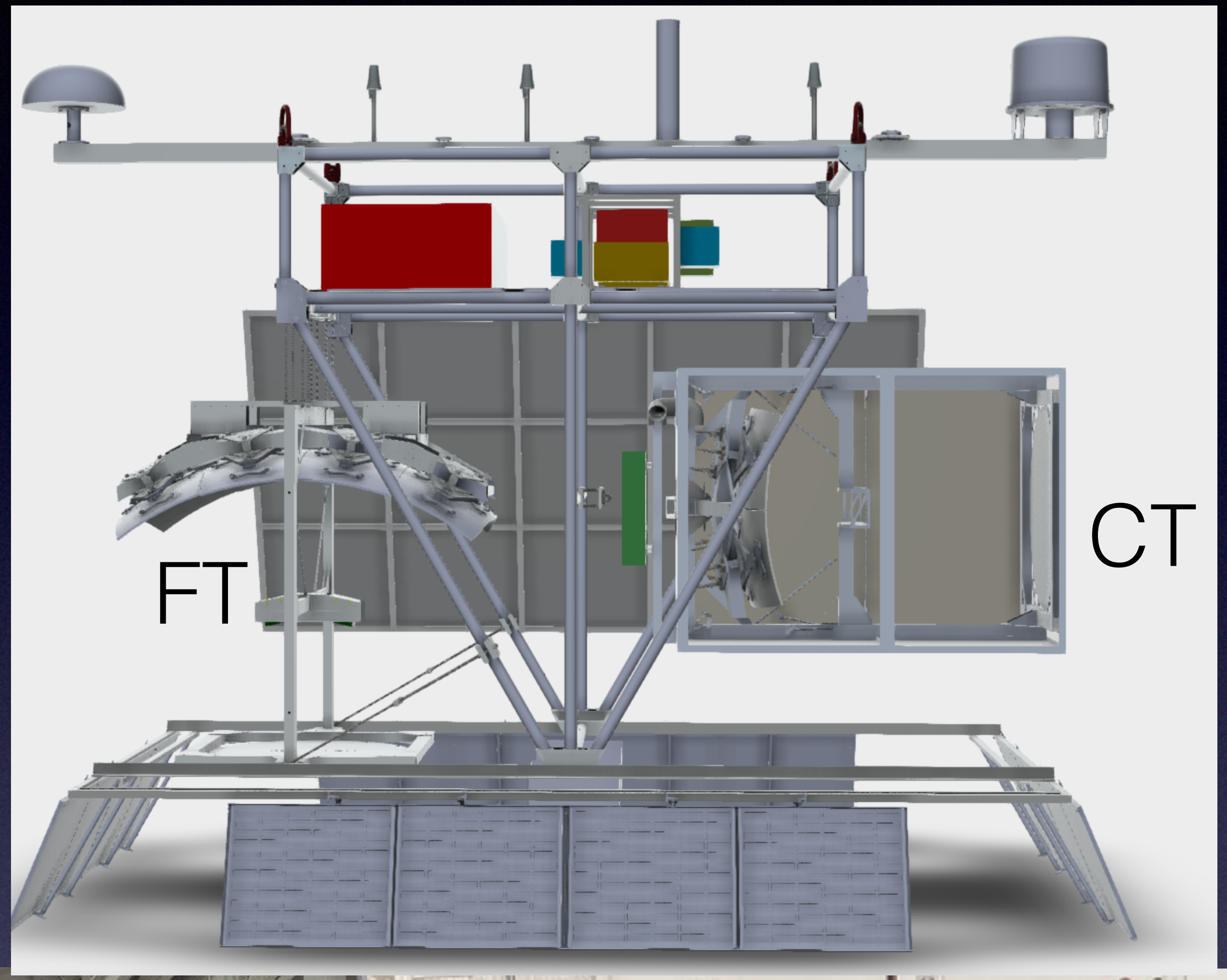


Earth Image Credit: Google Earth

EUSO-SPB2

Extreme Universe Space Observatory on a Super Pressure Balloon 2

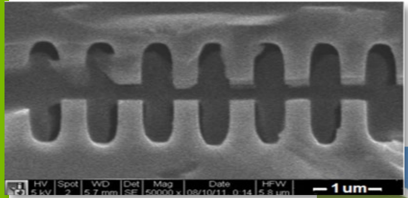
- Pathfinder project for POEMMA and other suborbital and space-based experiments using the fluorescence and optical Cherenkov techniques.
- Consists of 2 innovative telescopes—fluorescence telescope for observing UHECRs and a Cherenkov telescope for observing above-the-limb CRs and Earth-skimming ν_τ's
- Launch planned for Spring 2023 from Wanaka, NZ
- Potential for 100-day flight at 33 km altitude



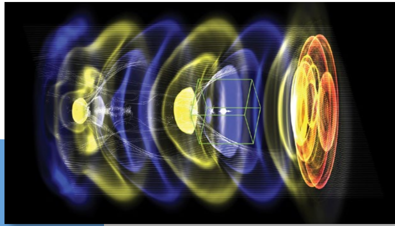
Collaborators: *University of Chicago, Colorado School of Mines, NASA/GSFC, NASA/MSFC, University of Alabama, Huntsville, Lehman CUNY, Georgia Tech, ASI, INFN (Rome, Torino, Palermo, Napoli), CNES (APC-Paris), RIKEN (Tokyo), et al.*

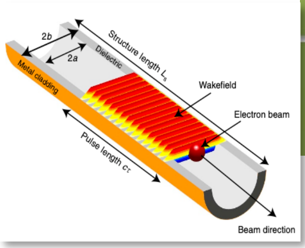
Xueying Lu
NIU & ANL

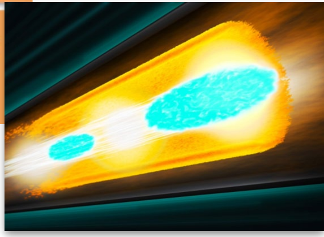
Advanced Accelerator Concepts (AAC) for Future Colliders



Driver \ Medium	Structure	Plasma
Laser Pulse	Dielectric Laser Accelerator DLA	Laser Wakefield Accelerator LWFA
Particle Bunch	Structure Wakefield Accelerator SWFA	Plasma Wakefield Accelerator PWFA







AAC technologies R&D

Overarching goal: efficiently harness the interaction of charged particles with extremely high EM fields to reach ultra high acceleration gradients (GeV/m)

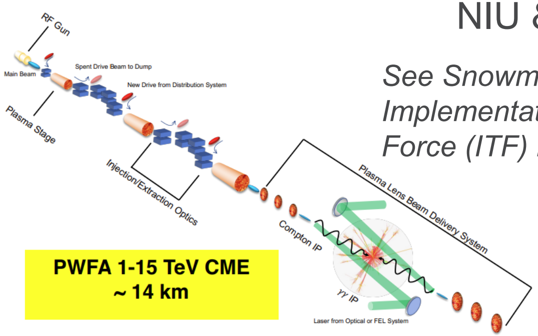
High gradient → Compact linear colliders

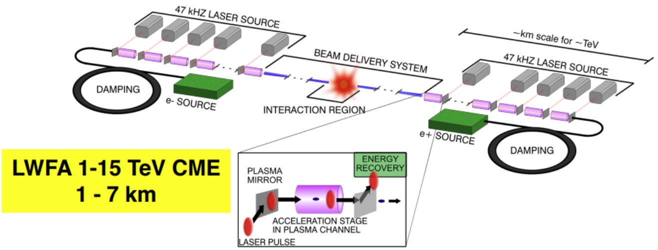
Towards a 10 TeV lepton collider

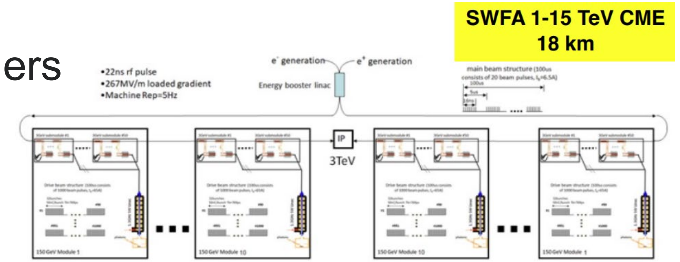
Xueying Lu
NIU & ANL

See Snowmass Implementation Task Force (ITF) Report

- AAC is a promising option for a multi-TeV lepton collider
  - Extending the energy reach of linear colliders
  - Compact enough for a US site
  - Potential reduction in power consumption & environmental impact
- Rapid progress recently with great scientific visibility
  - High gradient and high power structures
  - Advanced electron sources for bright beam production
  - Bunch shaping for efficiency improvement
  - Multi-GeV acceleration in a single stage
  - Staging, and many more
- Significant development still required for 10 TeV lepton colliders
  - AAC challenges to address: high repetition rate, high wall-plug efficiency, beam emittance preservation over stages, e^+ acc. …
  - Continued and enhanced R&D, upgrades to US Test Facilities







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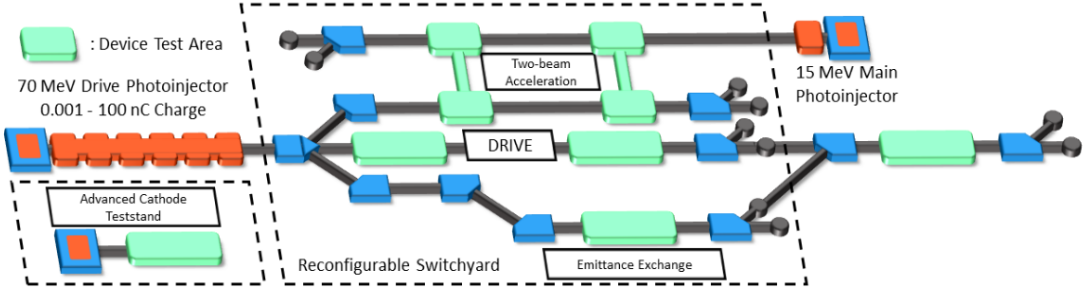
AAC for workforce of future colliders

- AAC has been building a strong workforce for future colliders
  - Students are being drawn into the field
    - Recent data point: at AAC'22 Workshop, 96 students (37%) out of 258 registrants
  - Unique training opportunities to learn about "the best of both worlds"
- Foster and deepen collaboration between national labs and universities
  - Capitalizing on premier US Beam Test Facilities



Welcome to the Argonne Wakefield Accelerator (**AWA**)

US center for SWFA research

The Feasibility of In-Ice Askaryan Radio Neutrino Detectors

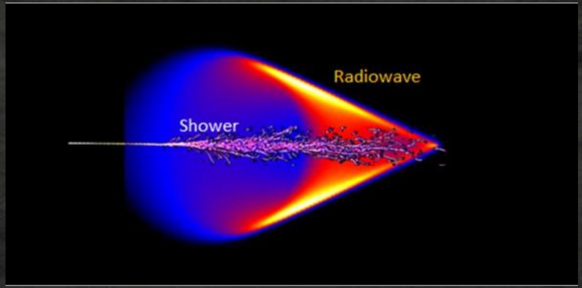
P5 ANL Town Hall 03.23.23

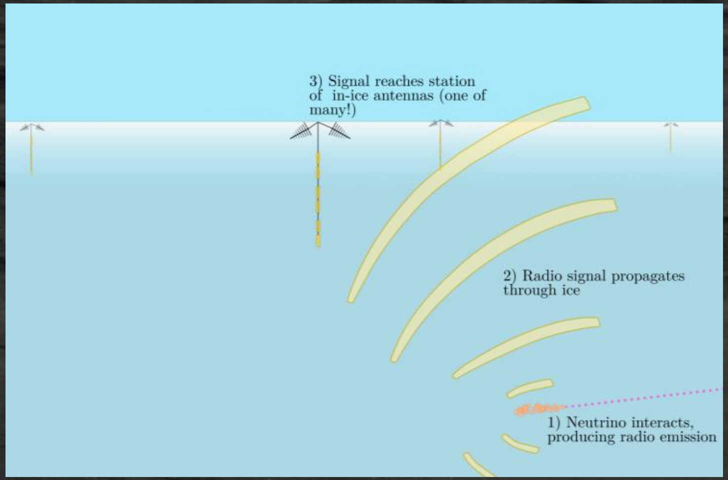
Cosmin Deaconu (UChicago) and Kaeli Hughes (PSU)

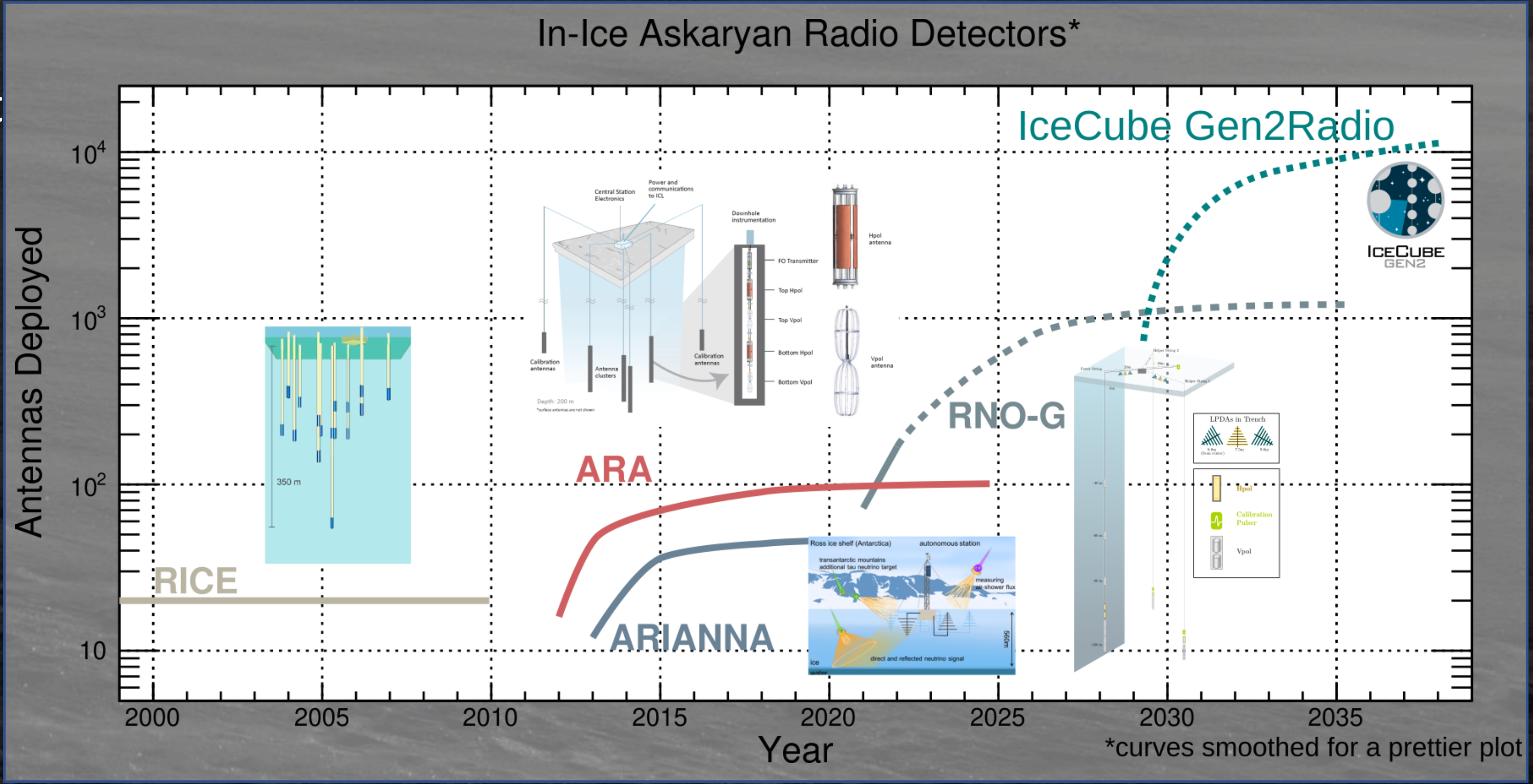
Closed caption box size

In-ice Radio Detection of UHE Neutrinos

- In-ice Askaryan radio detectors measure radio emission from neutrino-induced cascades in radio-transparent polar ice, allowing efficient instrumentation of the large volumes necessary to detect UHE (>100 PeV) neutrinos.
- Following pioneering work by earlier detectors (RICE, ARA, ARIANNA), the first mid-scale in-ice radio neutrino detector (RNO-G) is now being constructed.
- Detecting significant numbers of UHE neutrinos under many flux models will require a very large detector, like IceCube Gen2Radio.
- We believe that all the pieces are in place for a large-scale detector







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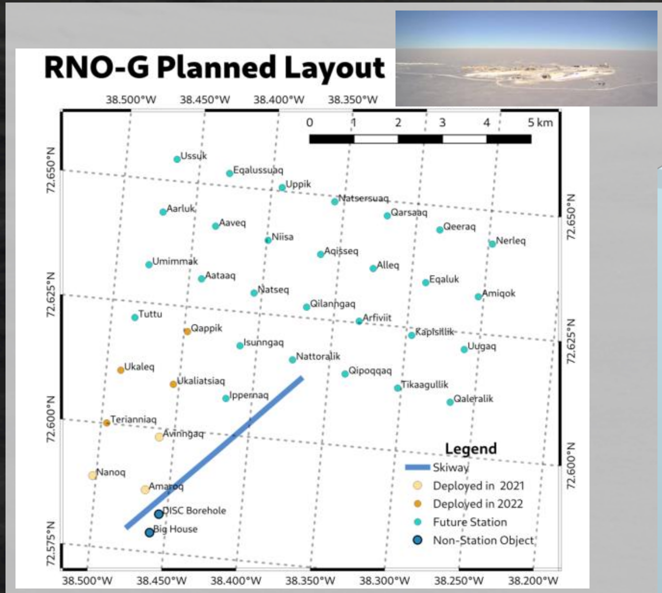
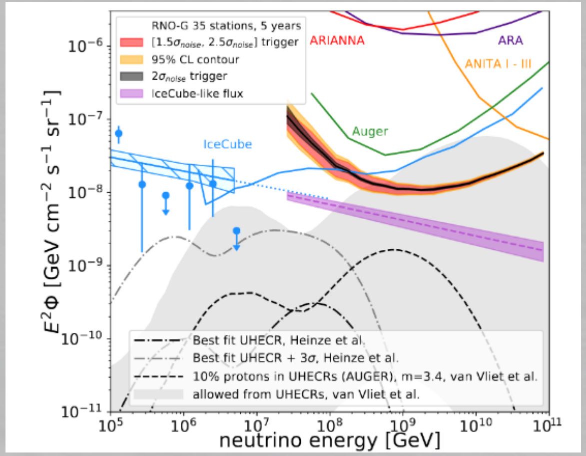
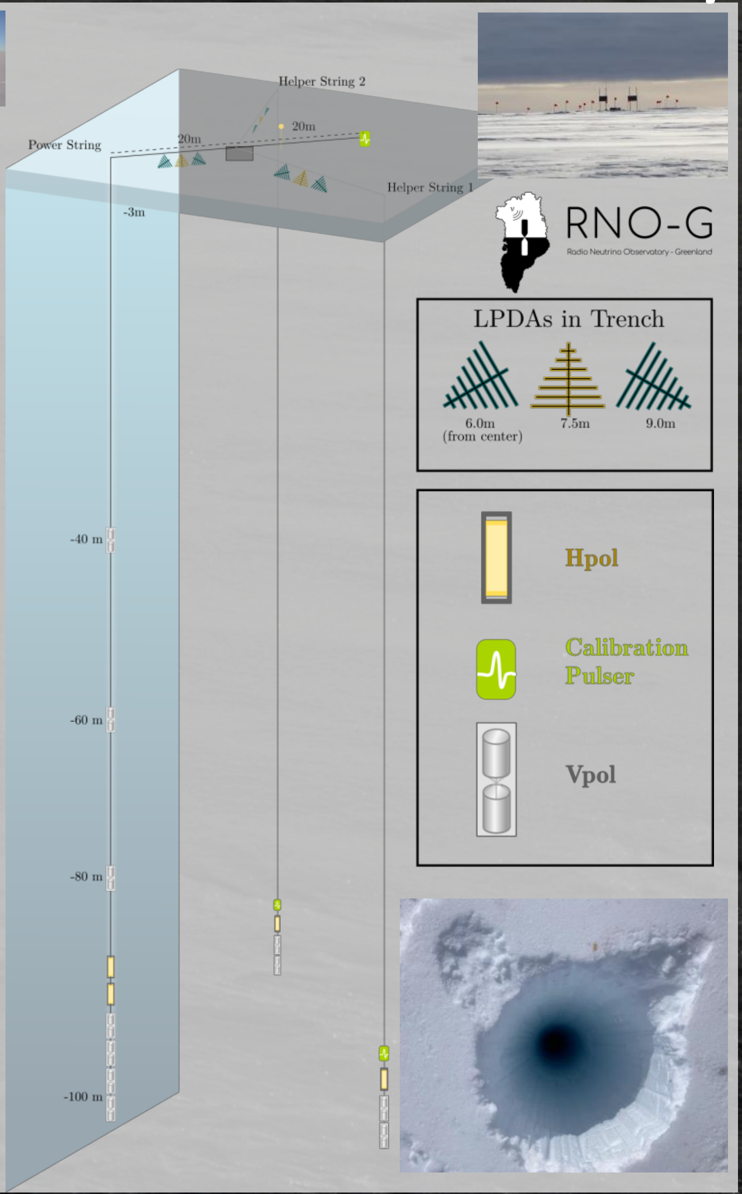
RNO-G demonstrates the scalability of in-ice radio







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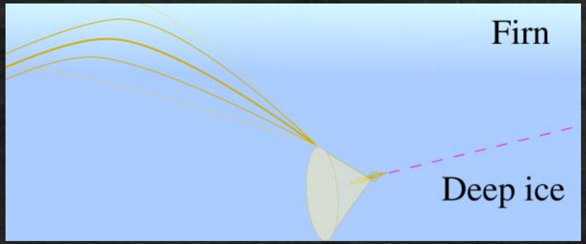
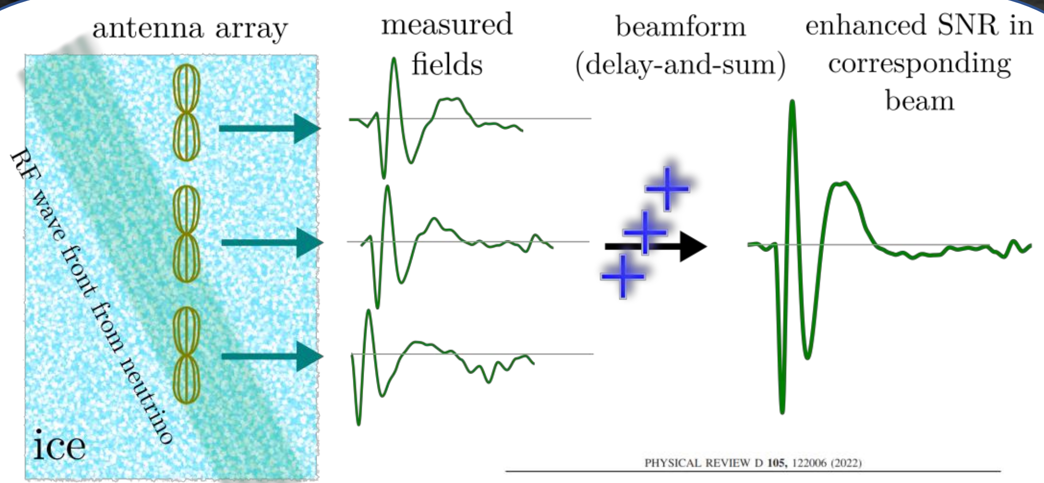
- The Radio Neutrino Observatory – Greenland (RNO-G) is a radio array being deployed in the Greenlandic ice sheet near NSF's Summit Station
- RNO-G is the first mid-scale Askaryan detector and has a realistic chance to detect the first UHE neutrinos.
- RNO-G has significant heritage from earlier experiments but has implemented significant advances in scalable electronics, deployment and operations.
- Optimized "hybrid" station design with 15 deep and 9 shallow antennas serves as the basis of the IceCube Gen2Radio design.
- International collaboration (US, BE, DE, SE, NL)

Reducing the energy threshold with phased arrays

- Deep antennas are more sensitive (due to ray-bending in shallow ice), but high-gain antennas don't fit in boreholes.



- Solution: synthesize high-gain antennas in boreholes using electronically-steered phased arrays to lower detection threshold, increase visible volume.
- Technique demonstrated at Pole with prototype as part of ARA; adopted as main-trigger by RNO-G, PUEO and IceCube Gen2Radio.
- Proof-of-concept analysis of ARA prototype demonstrates existence of low-background searches with high analysis efficiency.

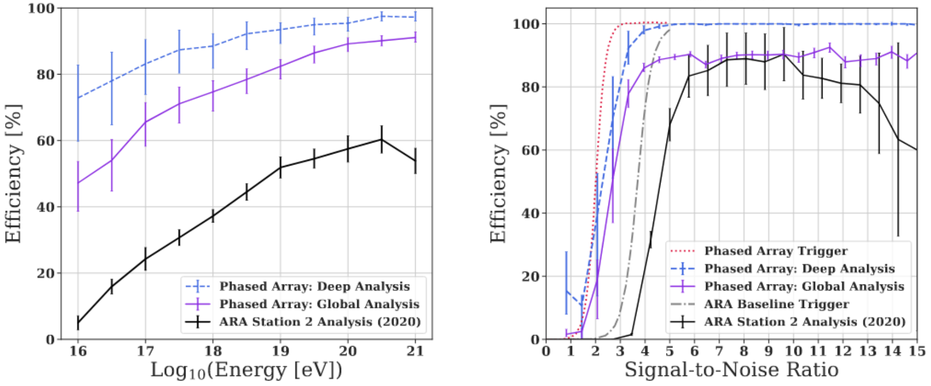



PHYSICAL REVIEW D **105,** 122006 (2022)

Low-threshold ultrahigh-energy neutrino search with the Askaryan Radio Array

P. Allison,[1] S. Archambault,[2] J. J. Beatty,[1] D. Z. Besson,[3,4] A. Bishop,[5] C. C. Chen,[6] C. H. Chen,[6] P. Chen,[6] Y. C. Chen,[6] B. A. Clark,[7] W. Clay,[8] A. Connolly,[1] L. Cremonesi,[9] P. Dasgupta,[10] J. Davies,[9] S. de Kockere,[11] K. D. de Vries,[11] C. Deaconu,[8] M. A. DuVernois,[5] J. Flaherty,[1] E. Friedman,[12] R. Gaior,[2] J. Hanson,[13] N. Harty,[14] B. Hendricks,[15,16] K. D. Hoffman,[12] E. Hong,[1] S. Y. Hsu,[6] L. Hu,[6] J. J. Huang,[6] M.-H. Huang,[6] K. Hughes,[8,*] A. Ishihara,[2] A. Karle,[5] J. L. Kelley,[5] K.-C. Kim,[12] M.-C. Kim,[2] I. Kravchenko,[17] R. Krebs,[15,16] Y. Ku,[15,16] C. Y. Kuo,[6] K. Kurusu,[2] H. Landsman,[18] U. A. Latif,[3,11] C.-J. Li,[6] T.-C. Liu,[6] M.-Y. Lu,[5] B. Madison,[3] K. Madison,[3] K. Mase,[2] T. Meures,[5] J. Nam,[2] R. J. Nichol,[9] G. Nir,[18] A. Novikov,[3] A. Nozdrina,[3] E. Oberla,[8] J. Osborn,[17] Y. Pan,[14] C. Pfendner,[19,20] N. Punsuebsay,[14] J. Roth,[14] D. Seckel,[14] M. F. H. Seikh,[3] Y.-S. Shiao,[6] A. Shultz,[3] D. Smith,[8] S. Toscano,[10] J. Torres,[1] J. Touart,[12] N. van Eijndhoven,[11] G. S. Varner,[21] A. Vieregg,[8] M.-Z. Wang,[6] S.-H. Wang,[6] Y. H. Wang,[6] S. A. Wissel,[15,16,22,23] C. Xie,[9] S. Yoshida,[2] and R. Young[3]

(ARA Collaboration)



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Hidden sector searches with low-energy neutrino scattering detectors

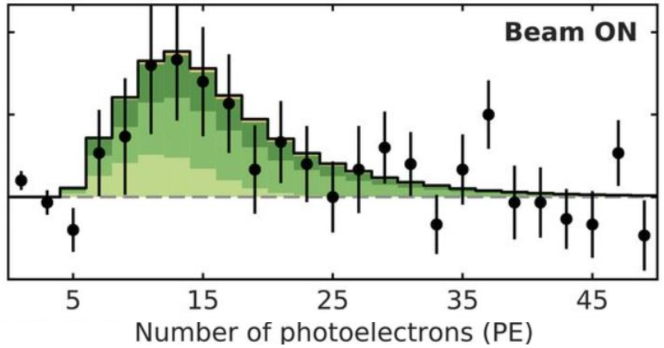
Dan Pershey, for the COHERENT experiment

P5 Town Hall

Argonne, Mar 23 2023

Coherent neutrino scattering at the Spallation Neutron Source

Spallation Neutron Source (SNS)
at Oak Ridge National Lab (ORNL)

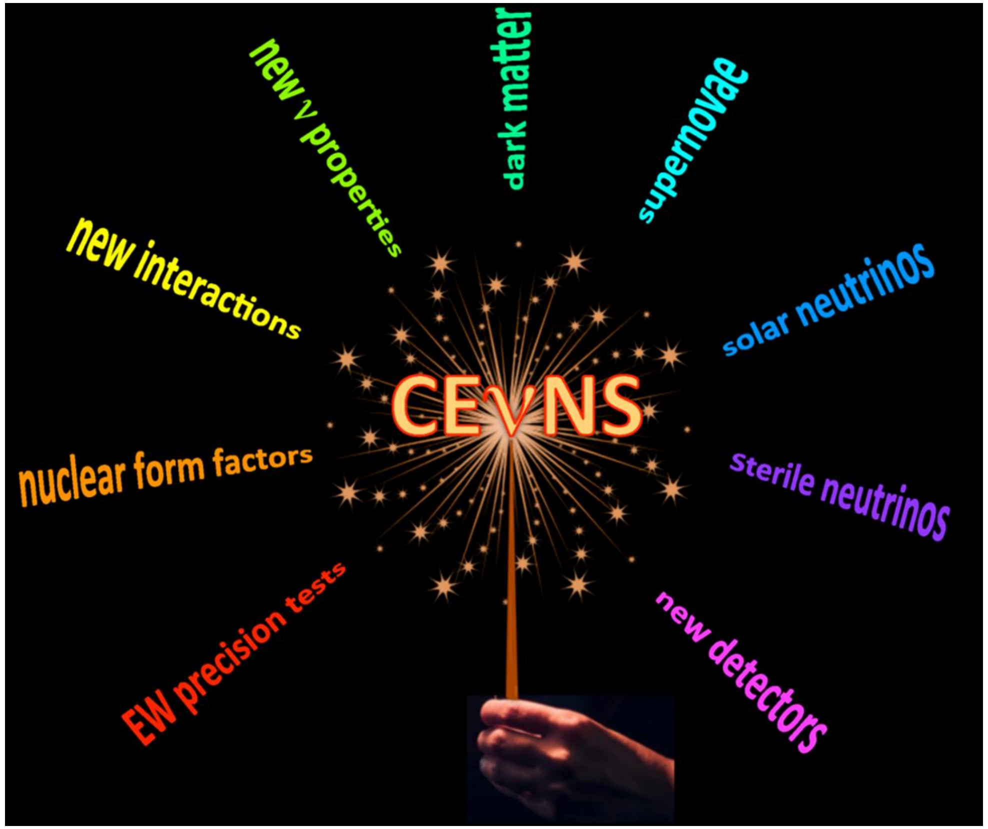


Coherent elastic neutrino-nucleus scattering (CEvNS)

First measurement: COHERENT (2017) with CsI[Na] scintillator

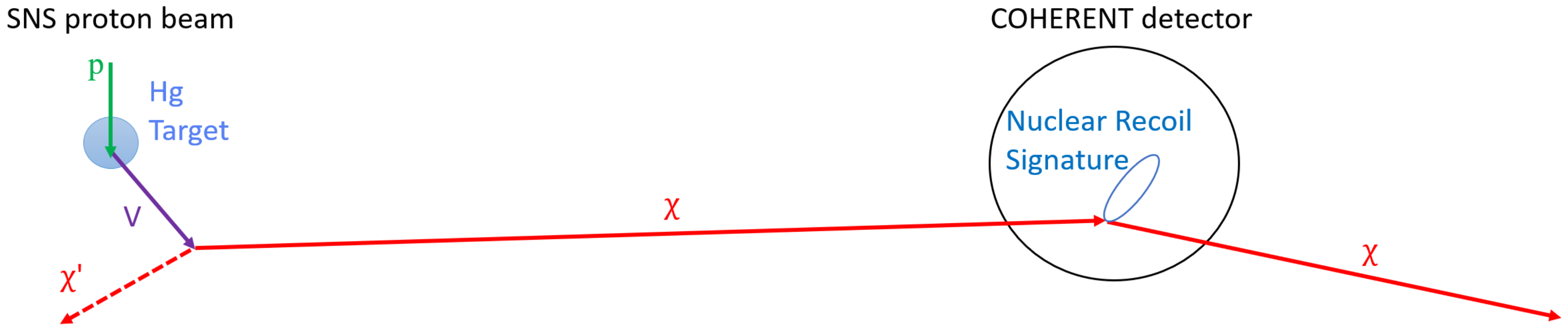
COHERENT, *Science* **357** 6356 (2017)

Applications of CEvNS measurements



E. Lisi, Neutrino 2018

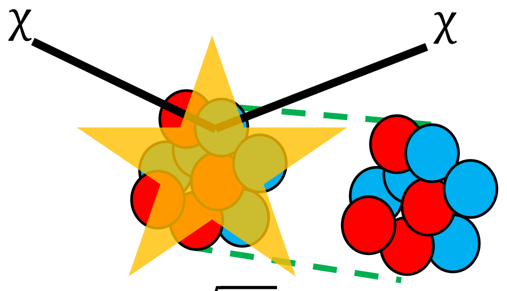
Searching for dark matter with CEvNS detectors



A typical beam dump experiment

Vector DM portal => production of DM comes from meson decay in flight: $\pi^0 \rightarrow V\gamma$

CEvNS detectors get the best of both worlds!



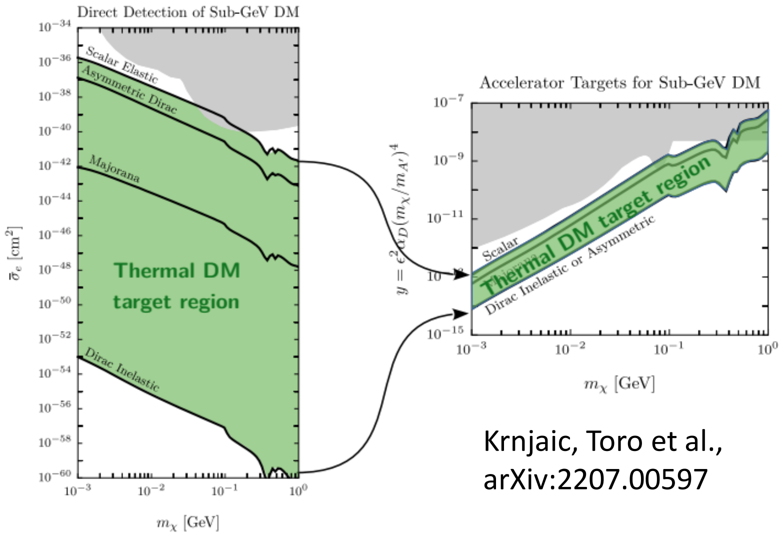
$$\lambda = h/\sqrt{Q^2} \gg R_p$$

Detect DM via coherent scattering – large cross section

Advantage: direct detection experiments (and COHERENT!)

DM at accelerators is relativistic and less sensitive to DM nature

Advantage: accelerator-based searches

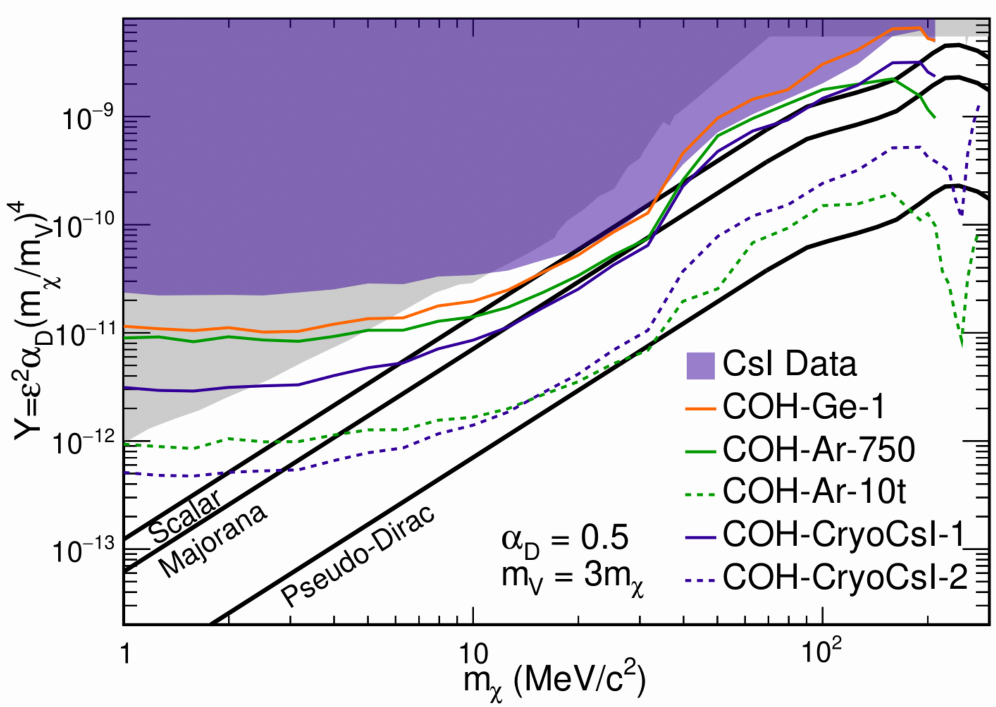


Krnjaic, Toro et al., arXiv:2207.00597

Future potential for DM discovery

Key: construction of second target station at the SNS allows detector hall for 10t-scale neutrino experiments

Several potential CEvNS detector technologies – e.g. an argon scintillation calorimeter



Future CEvNS detectors at the SNS allow 1000x larger exposure than current COHERENT datasets

Allows aggressive probe of scalar and fermion sub-GeV DM with a direct detection experiment